Commissioning the Large Hadron Collider

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Outline

- Why the LHC?
- What does it look like?
- What is it made of?
- Commissioning
- What's next?

Why the LHC?

- **The "Standard Model" is successful but incomplete**
  - It does not explain particle mass, neutrino mixing, what happened to all the antimatter…
- **Mass:**
  - In the Standard Model, all masses are zero by a symmetry of the theory
  - Some interaction must break the symmetry
  - Modern theory: a force field accompanied by associated particles
  - Searching for the particle(s) at the LHC
- **$E = mc^2$**
- **Other symmetries and symmetry-breaking mechanisms**

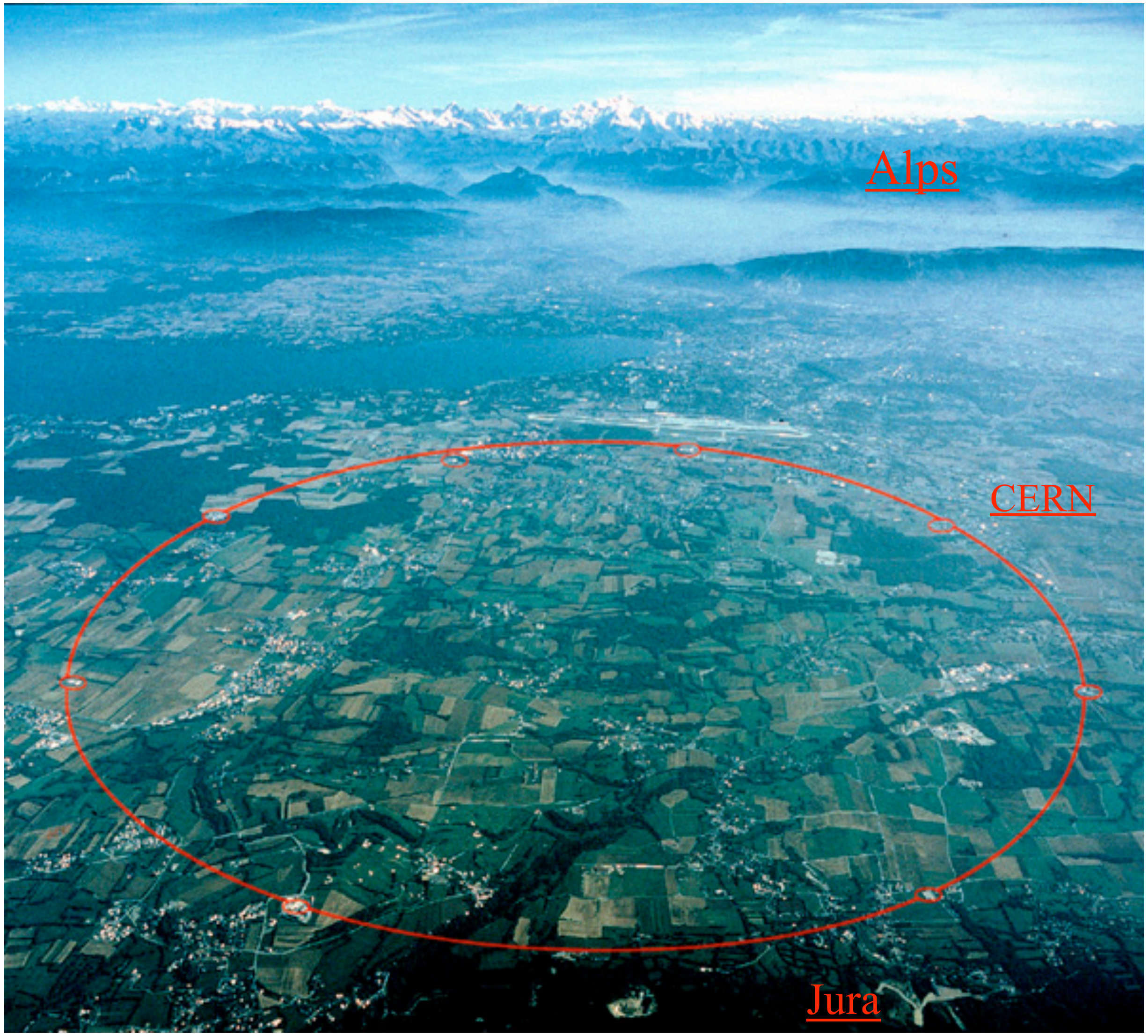
The Large Hadron Collider

- **A proton-proton collider**
  - Seven times the energy of the present biggest – The Tevatron @ Fermilab
  - Will probe the TeV mass scale and answer (we hope) many outstanding questions about the fundamental nature of the universe.
- **Built and operated by CERN, the European Center for Nuclear Research**
  - Located on the Swiss - French border near Geneva
- **The design and R&D for the LHC began 25 years ago**
  - In direct competition with the SSC, an even larger and higher energy collider planned by the U.S. and later canceled
- **It is being (re)-commissioned now and will start doing physics soon**

It's Huge, It's Complex, It's High-Tech

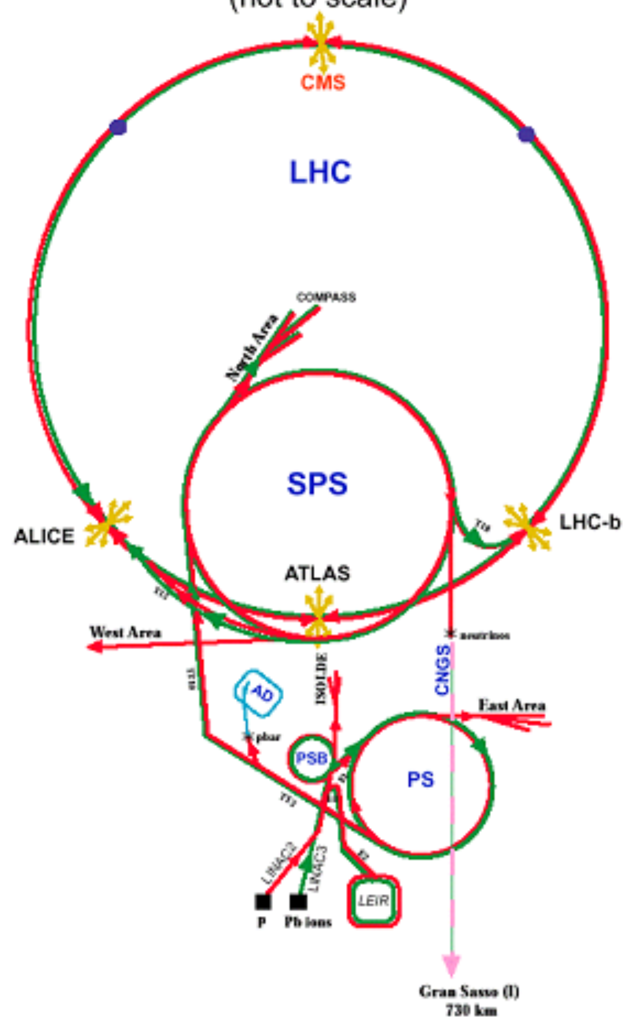
- **A proton-proton collider of unprecedented energy and size**
  - 7 TeV x 7 TeV = 14 TeV in the center of mass
  - 27 kM in circumference in a tunnel 50 m to 150 m underground
- **Over 10,000 magnets, most of them superconducting**
  - Including 1,700 of the highest field accelerator magnets ever built
- **Over 1,700 power-supply circuits**
  - With regulation of one per million
- **The largest helium cryogenic plants in the world**
  - All superfluid, using state-of-the-art cold compressors
- **Parts of it were collected from all over the world**
  - More than a dozen nations from outside the CERN member states contributed important parts of the LHC
- **The product of <u>size</u> x <u>complexity</u> x <u>technology</u> makes the LHC the most challenging scientific instrument ever built**

The LHC Site

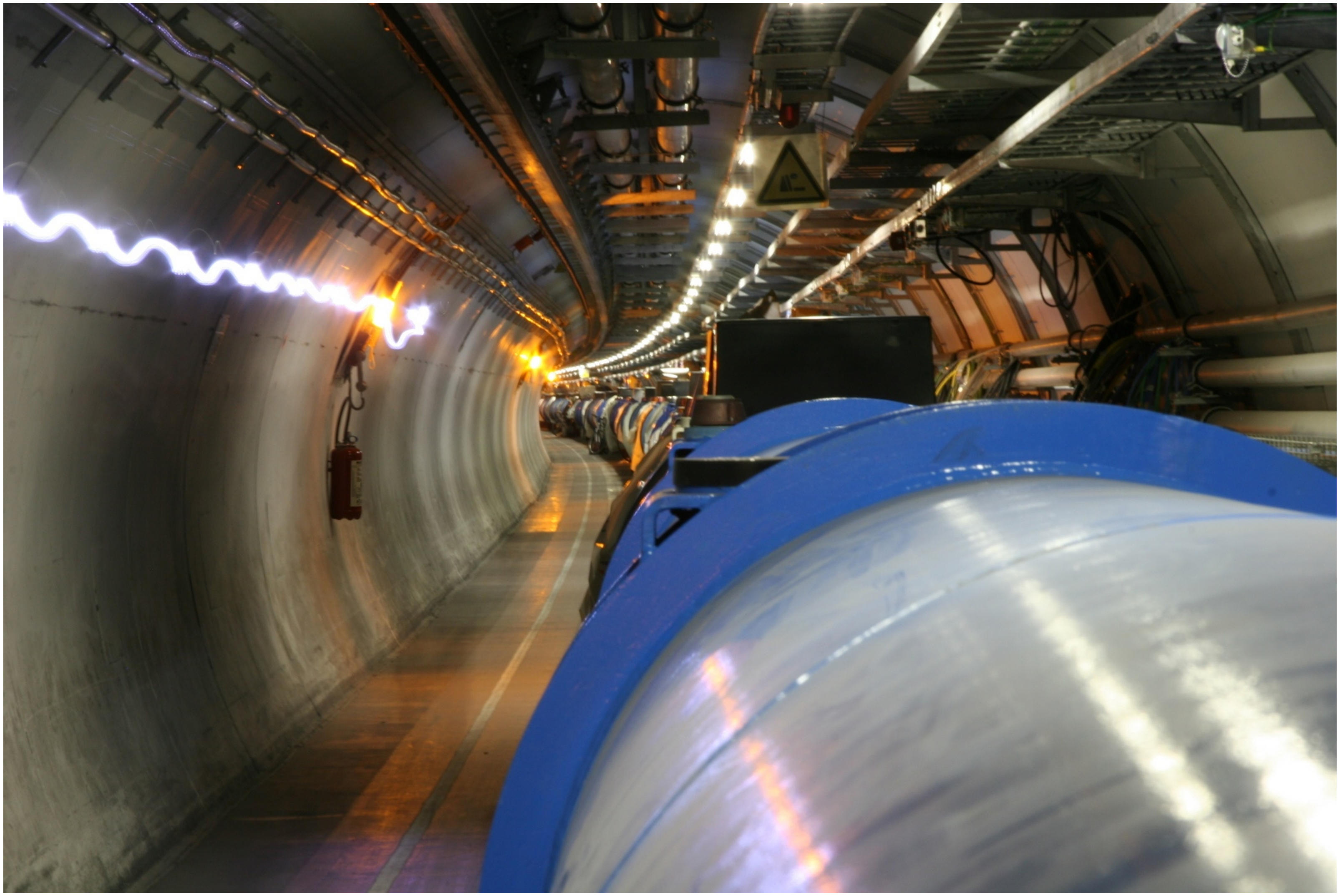


The Existing Accelerator Infrastructure

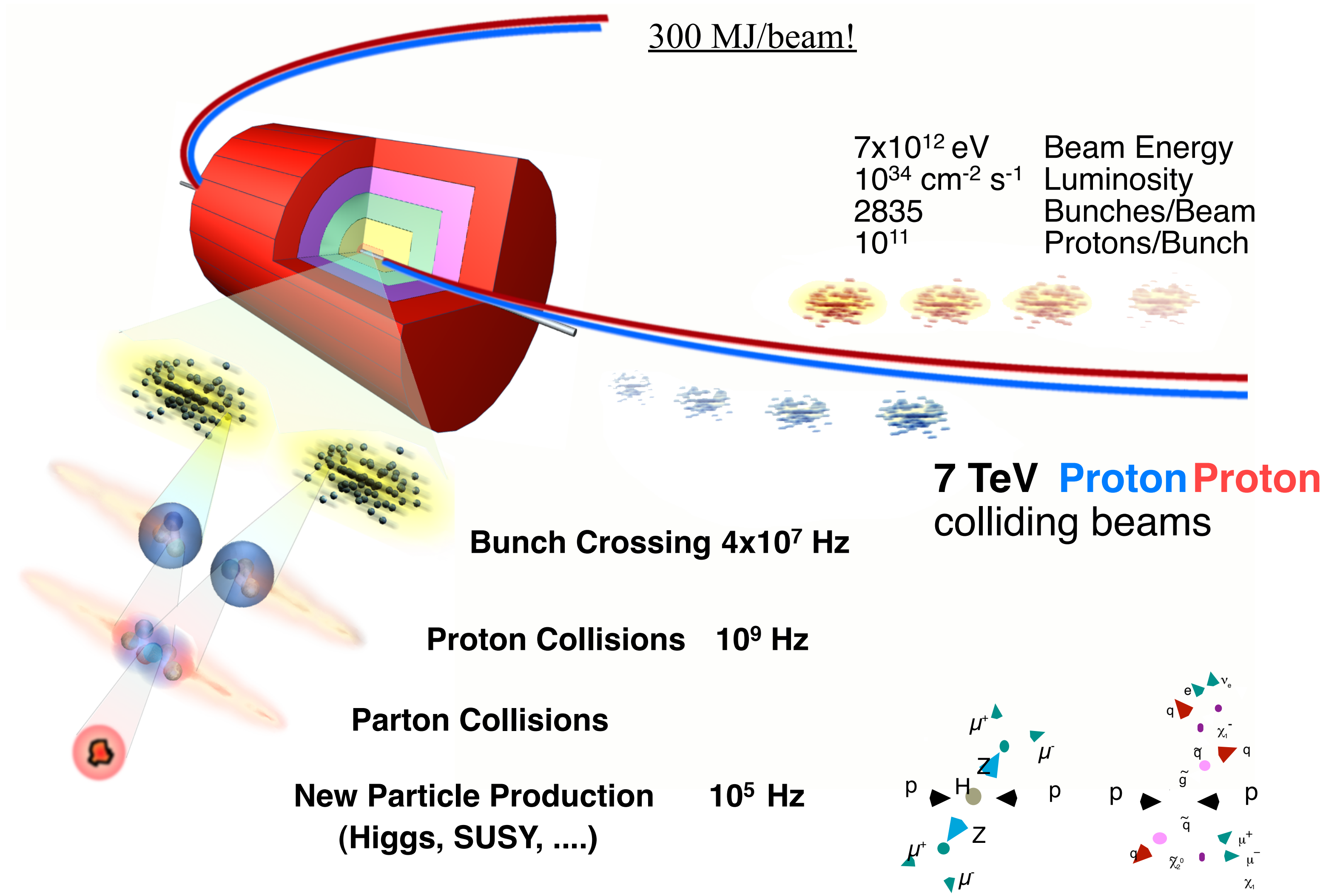
(not to scale)



Tunnel View



Some LHC Parameters



The Large Hadron Collider

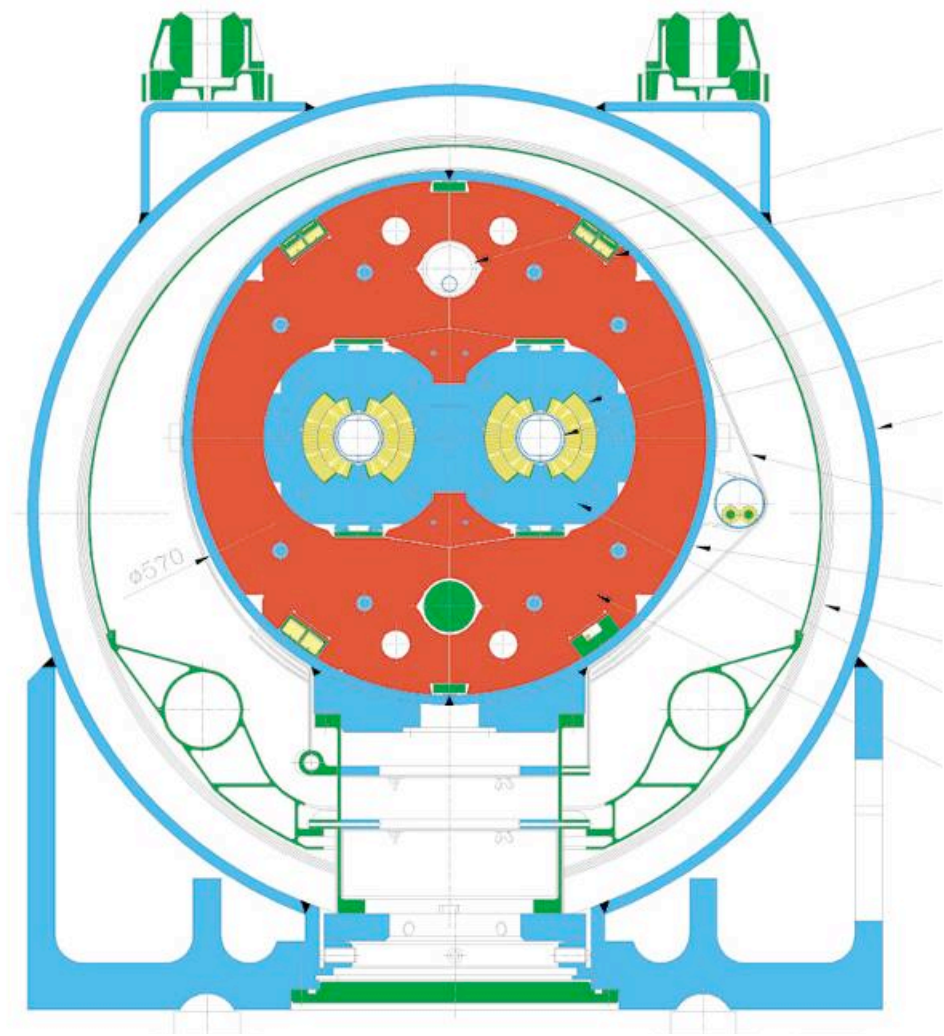
- **Why is LHC so big?**
  - The protons are bent around so that they will pass by RF cavities over and over again.
    - Because RF cavities are much more expensive than magnets
  - Each time they go through the RF cavities their energy is increased.
    - The magnet strength is increased in in synchronization with the beam energy to keep the particles in a small beam tube - a synchrotron
  - The ultimate energy is limited by the magnet strength and tunnel circumference

$$\mathbf{E_{beam} = eBR}$$

The Design Concept

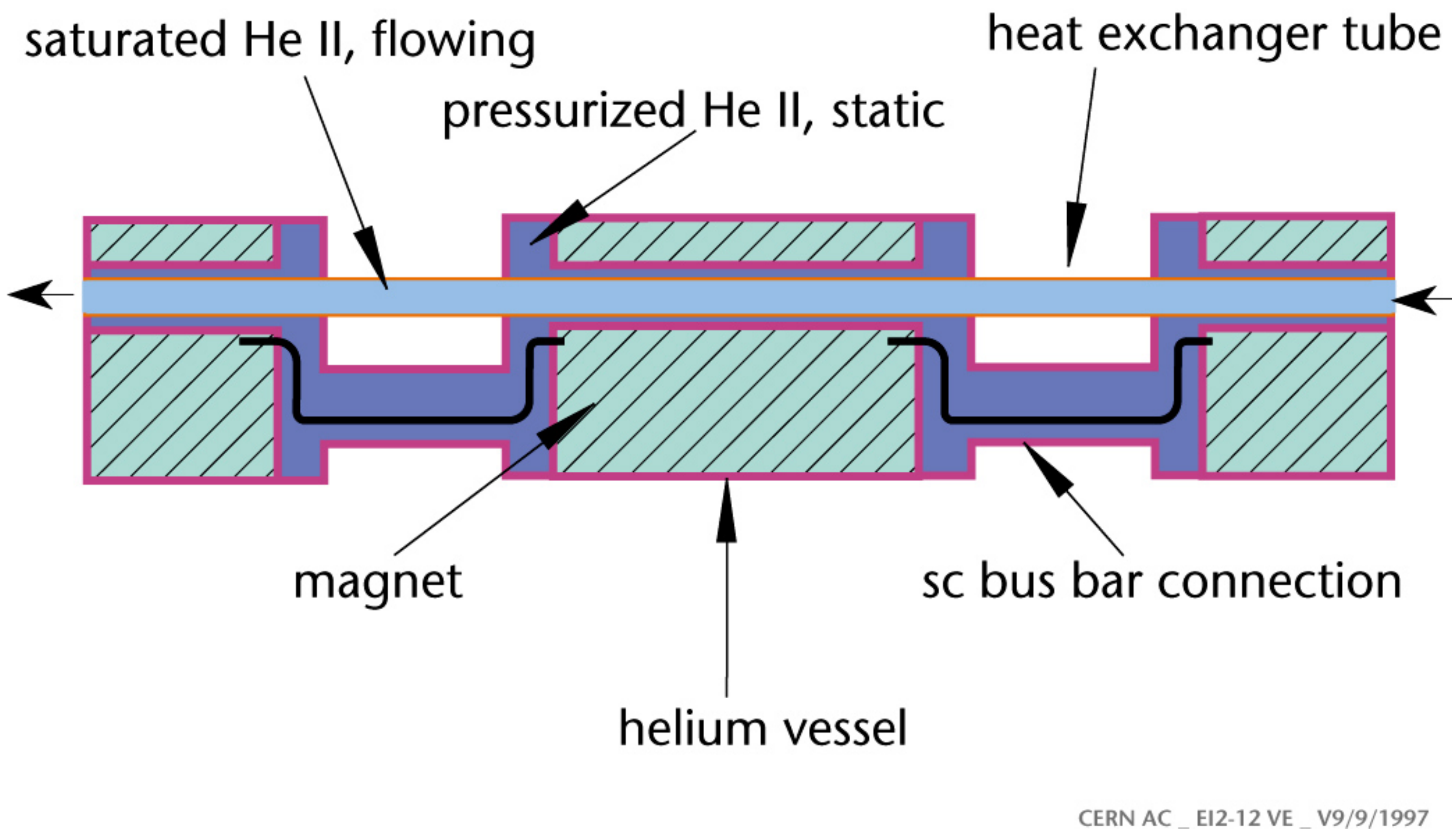
- **The first hurdle – how to achieve the highest possible magnetic field strength**
  - The tunnel already existed, thanks to LEP – the Large Electron-Positron Collider
    - This is a great cost advantage, but also a limit on energy and other design features
- **Two important early decisions**
  - Superfluid helium for lower temperature and higher field strength
  - Two-in-one magnets for cost savings and higher field
    - Two coil sets in one steel yoke and in one cryostat

LHC Main Dipole Cross Section



Cooling to Superfluid

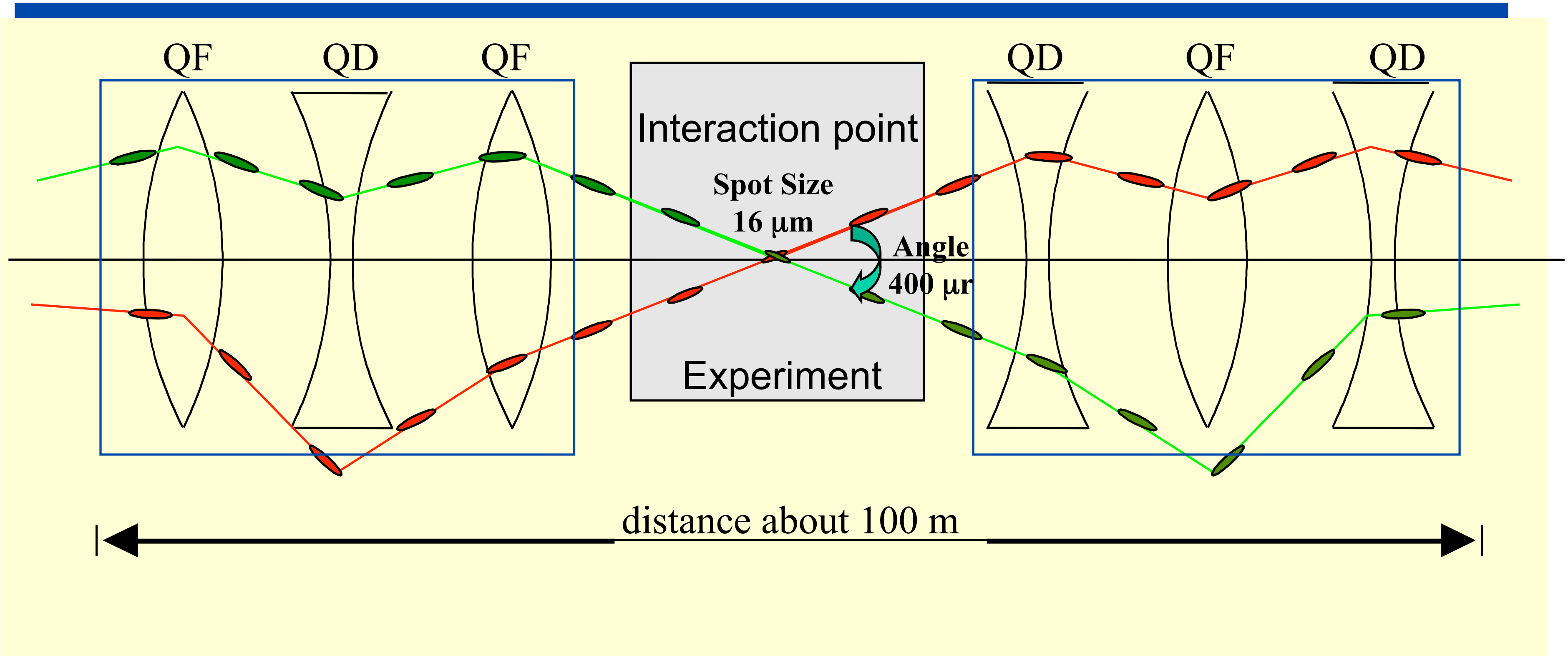
LHC magnet string cooling scheme



The Construction

- **How to build 10,000 magnets?**
  - Could not be done all by CERN
  - Many industrial contracts, all watched carefully
  - Lots of contributions from many nations
- **Much of the R&D and design done outside CERN**
  - An example is the inner triplet magnets designed & built in Japan and Fermilab.
- **A lot of travel, a lot of telephone time, a lot of Webex**

The Inner Triplet Magnets



The most challenging magnets in the LHC.

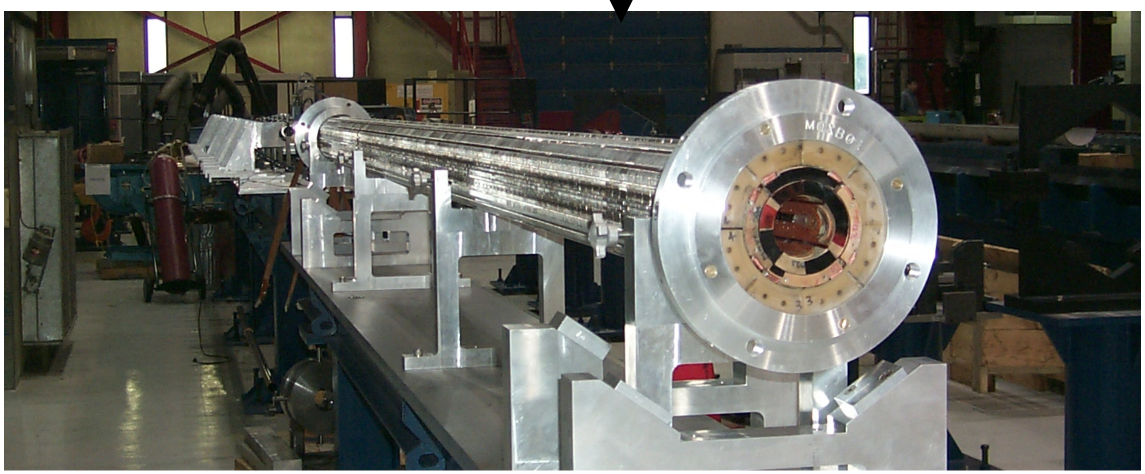
Made half in Japan, half at Fermilab

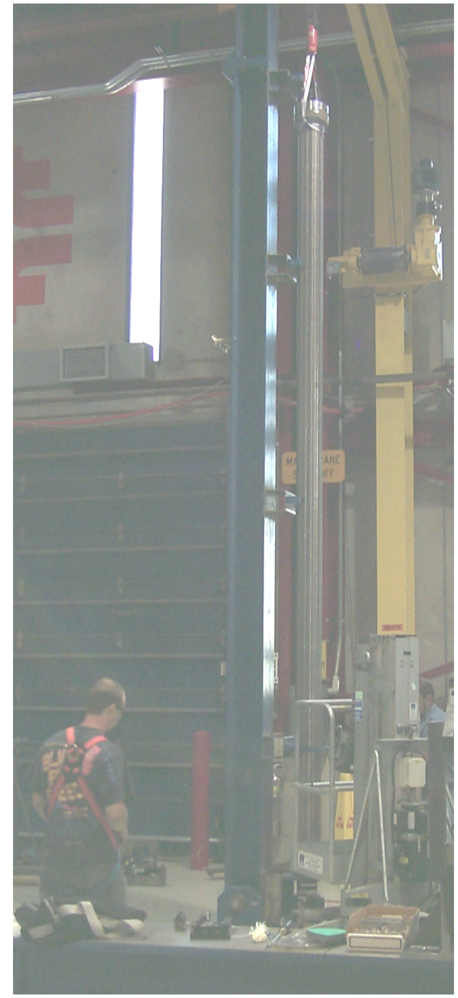
Requirements: Large aperture and high field,
Excellent field uniformity and alignment,
Must operate in a high radiation area

Collaring the Coils

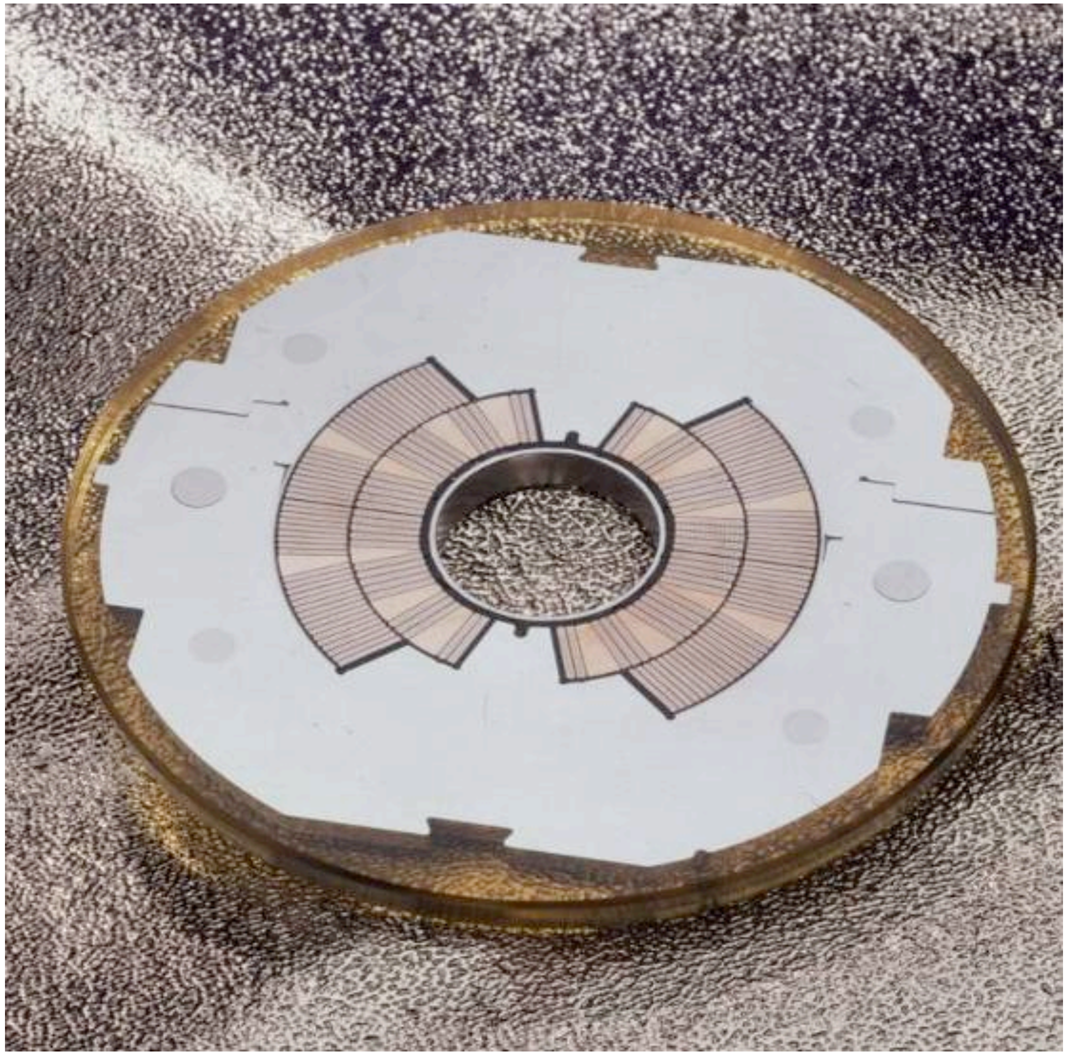
Coils in vertical collaring press

Collared coil ready for magnetic measurement

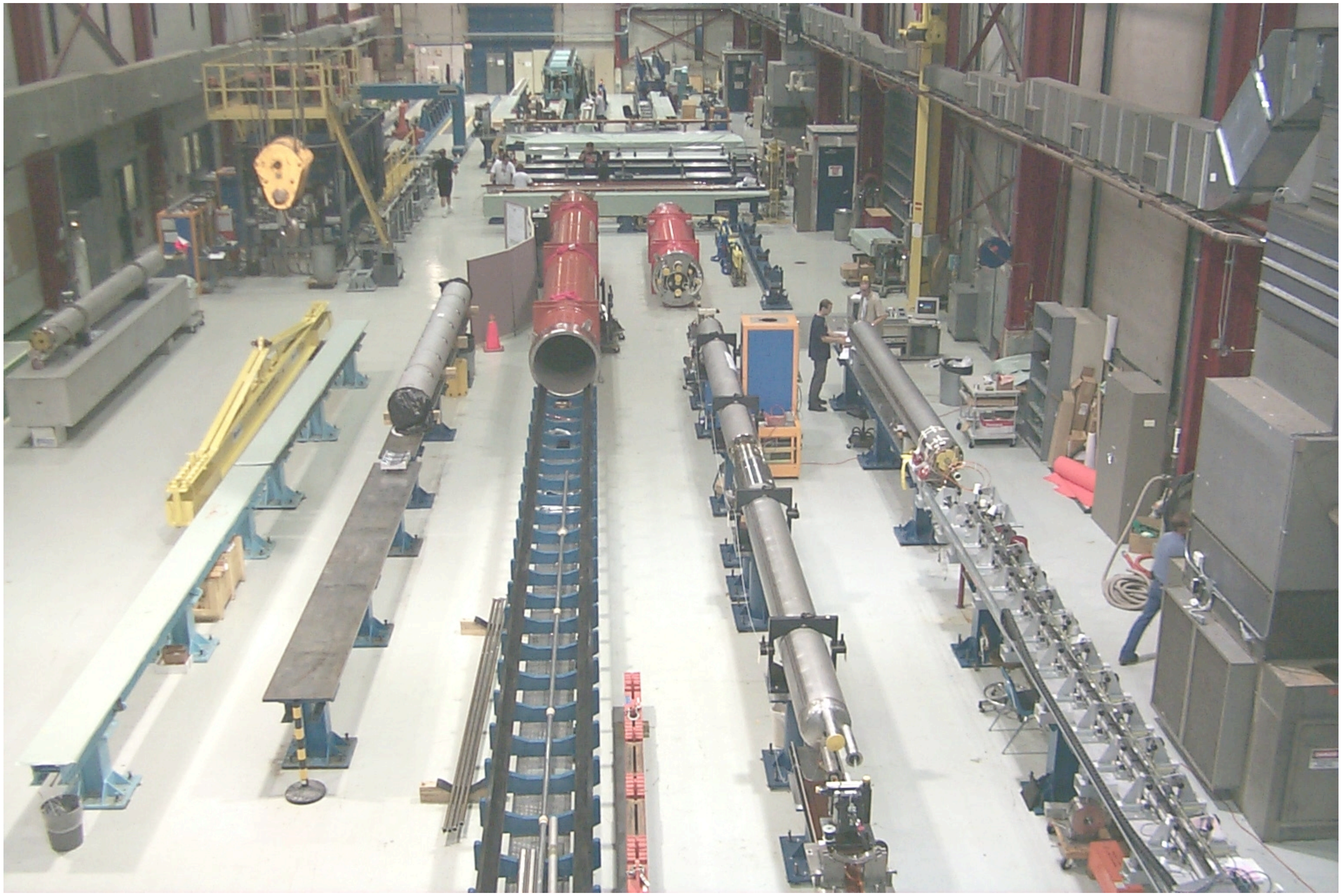




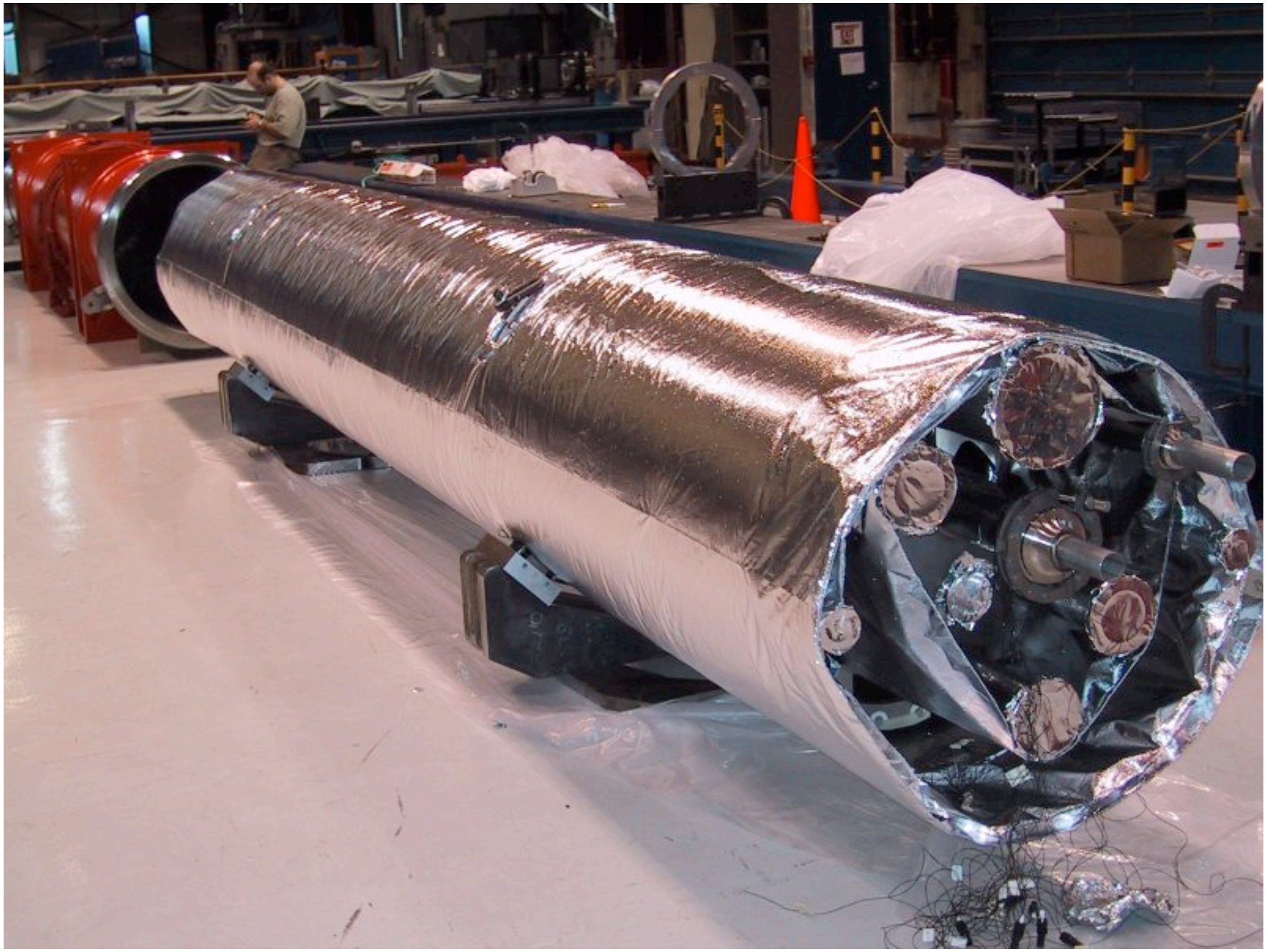
Cross Section of Finished Collared Coil



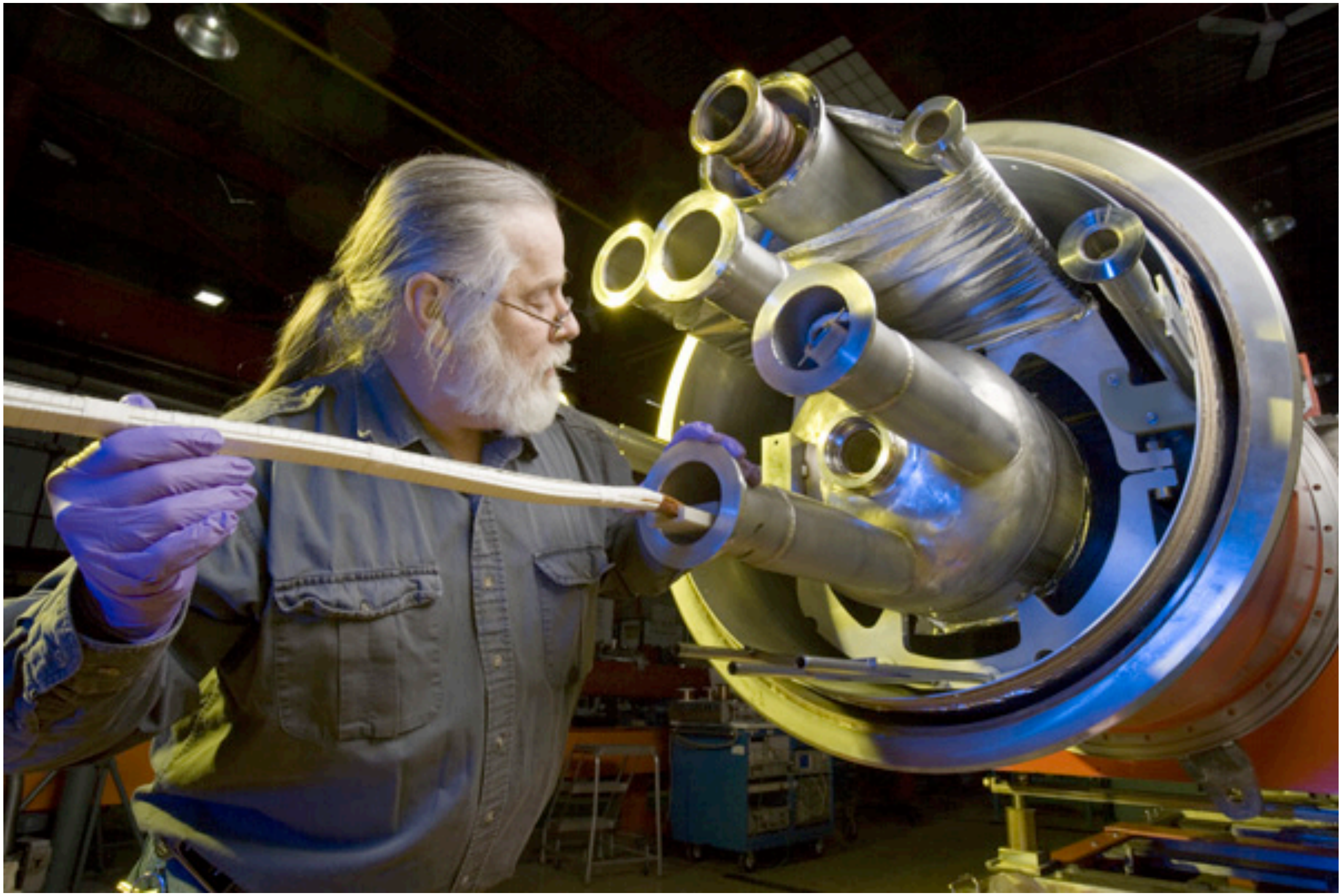
The Production Floor @ Fermilab in 2003



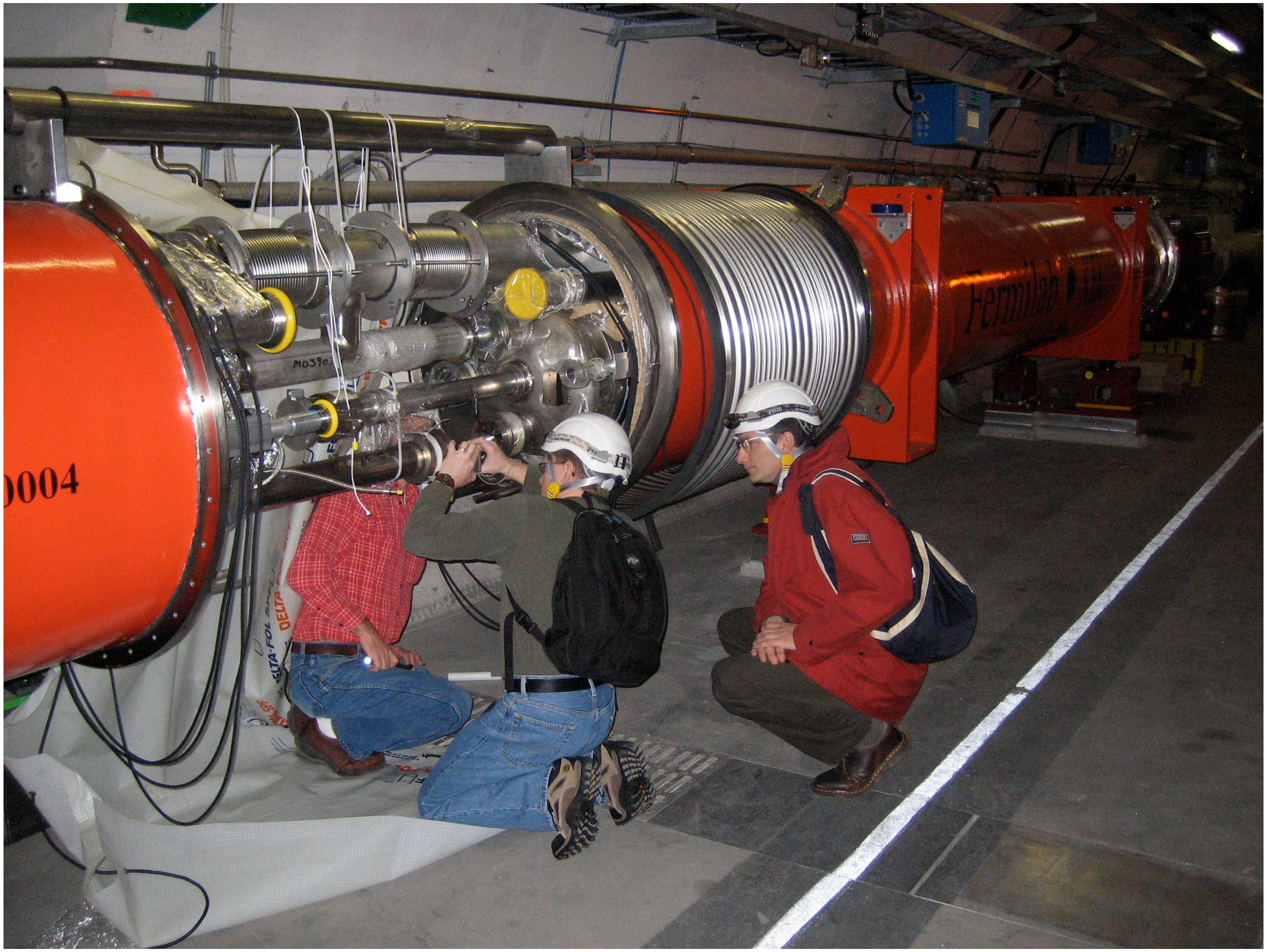
Ready for Insertion into Cryostat



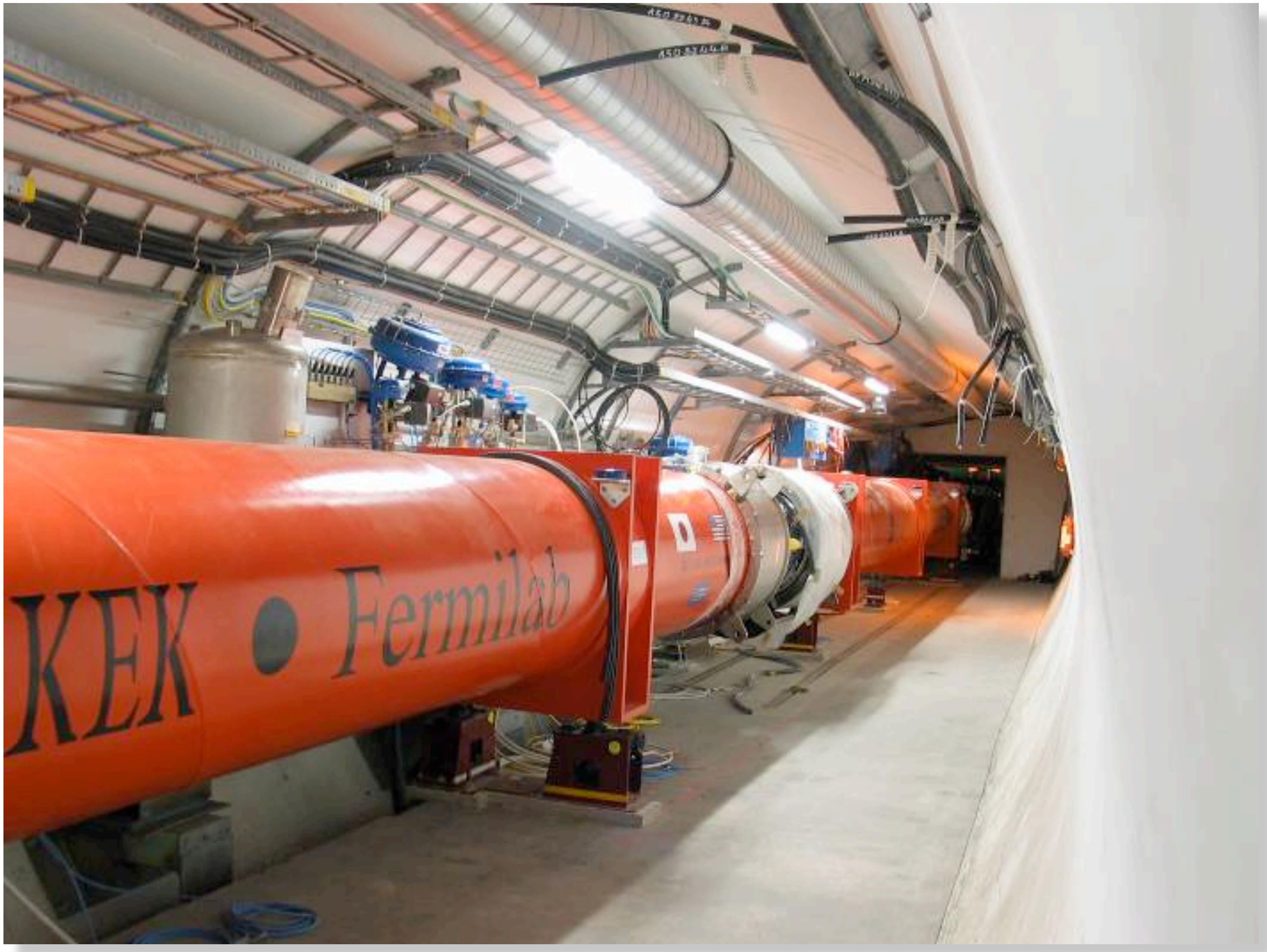
Some Final Touches



Installation of the Inner Triplet



The Inner Triplet

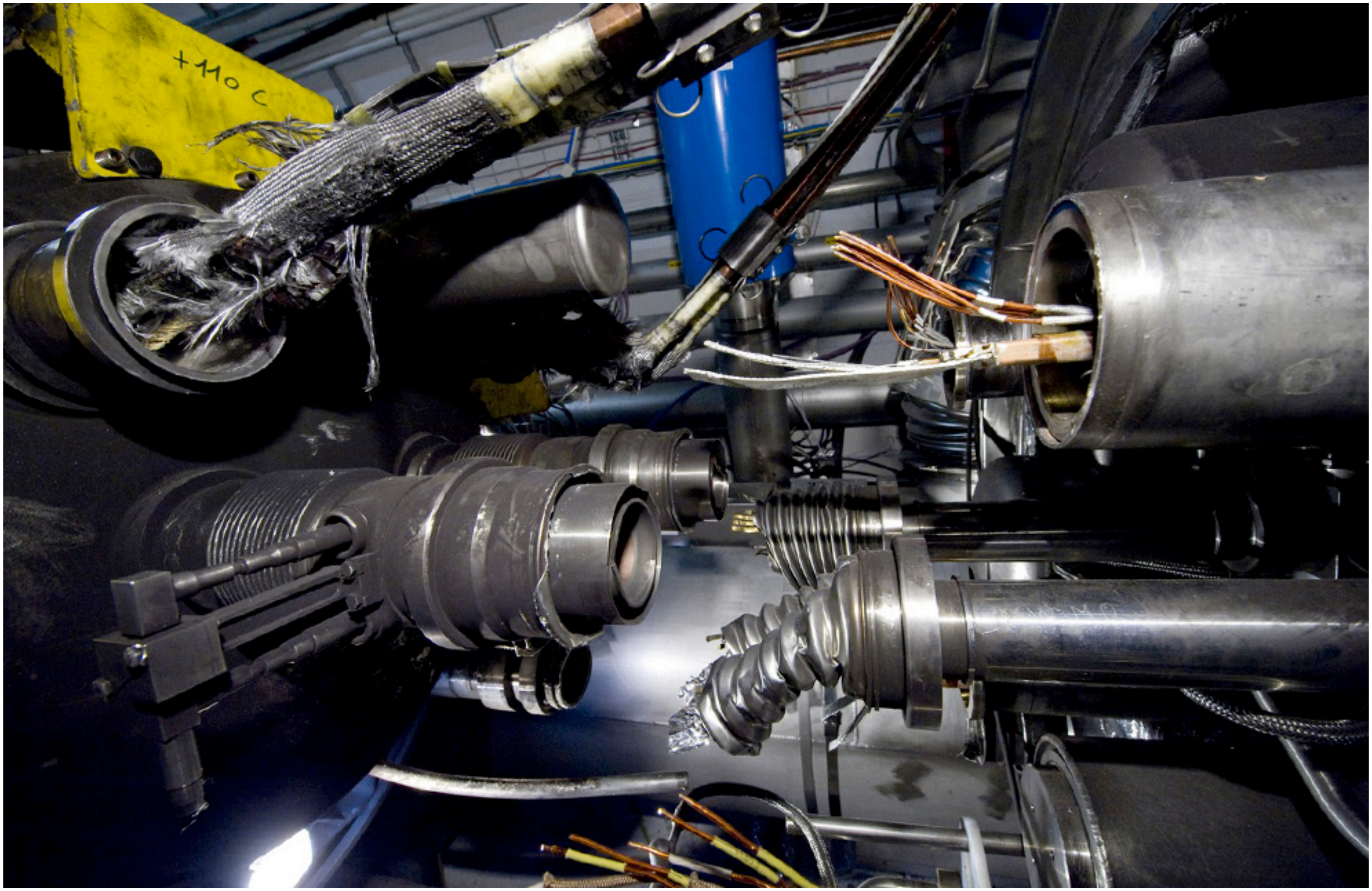


Commissioning from the Control Room

Commissioning

- **Hardware commissioning complete and first beam Sept. 10, 2008**
- **Everything was going great. Then…**
- **On Sept. 19, 2008 BOOM! What happened?**
  - An inter-magnet splice came apart at ~8000 A (no beam was circulating)
  - Energy stored in the LHC magnets is 5 GJ @ 8 kA (~ 11 GJ at 12 kA)
  - Energy stored in a sector of dipoles (energy extraction unit) ~600 MJ @ 8 kA
  - ~ 250 MJ went into the primary arc; the rest went into secondary arcs and the dump resistors
  - The arc pierced the helium containment vessel and beam tube
  - The pressure rise in the insulating vacuum space moved many magnets and sent debris (soot & superinsulation) down the beam tube

At location of arc



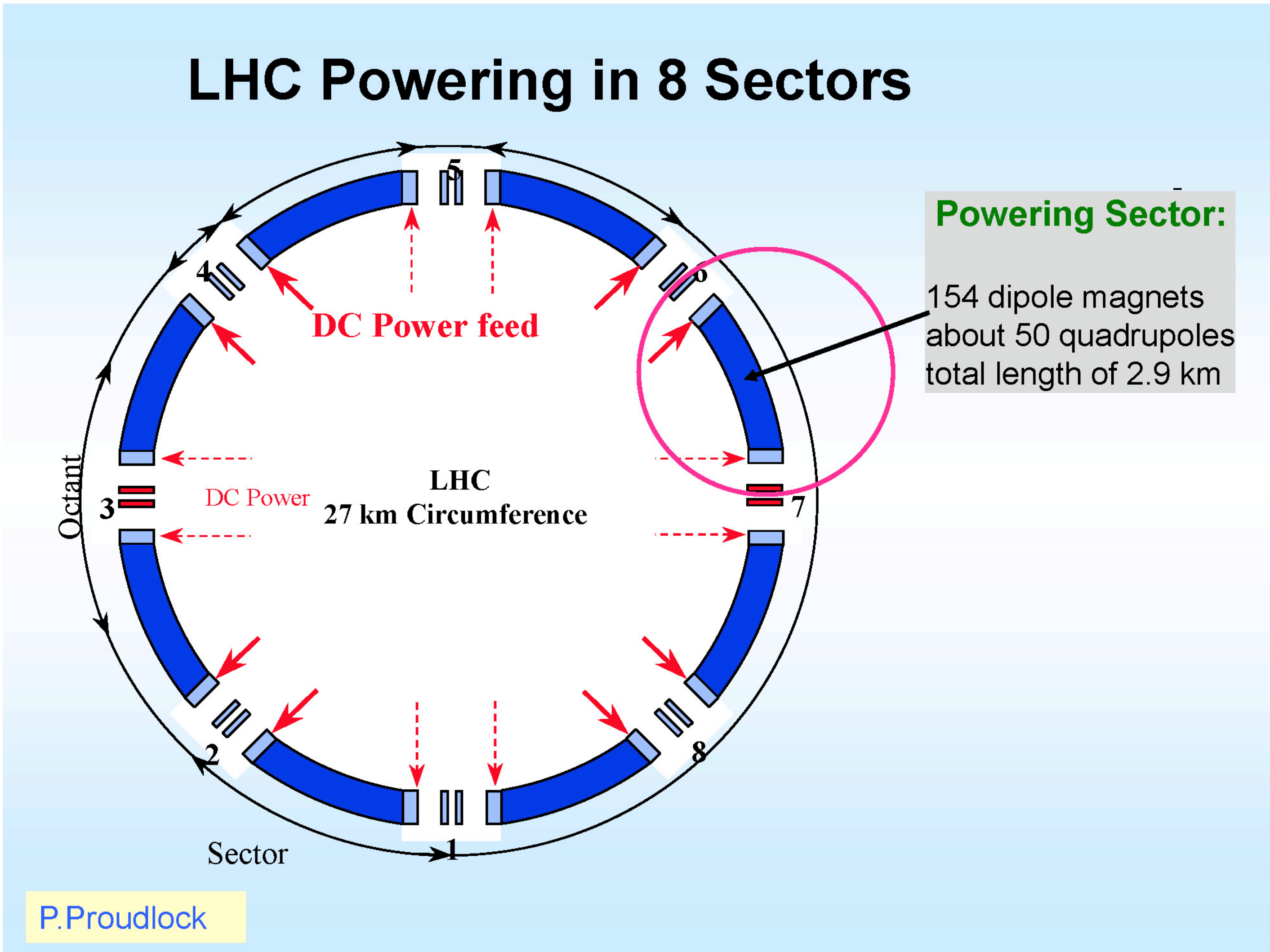
Magnets moved

Some magnets left stands

Summary of 19Sept08

- **In all, 54 magnets had to be repaired and replaced**
  - Installed more relief valves on vacuum space
  - Beam tube for 100s of meters had to be cleaned
- **Delayed commissioning by 18 months**
- **Complete fix will require another 1.5 years downtime in 2012-2013**
  - New problems were found that require modifications
- **LHC will operate at reduced energy until then**

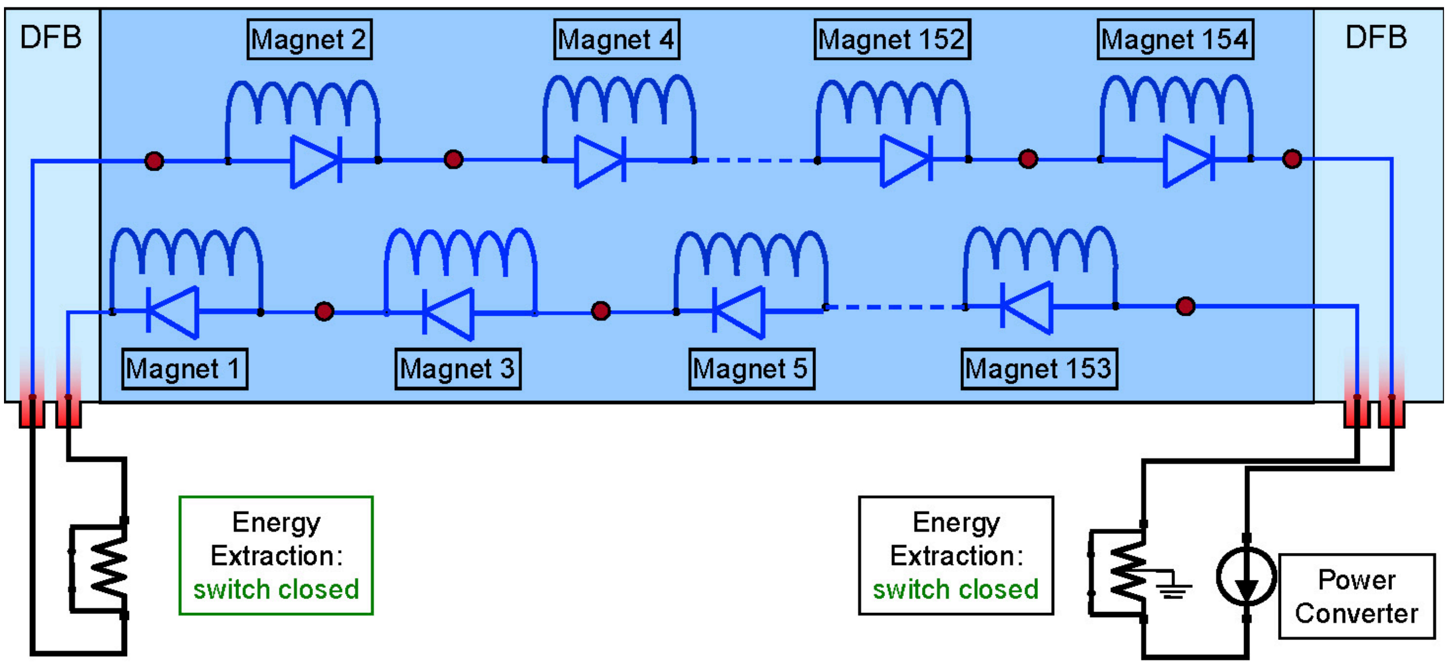
Powering the LHC (1)



Powering the LHC (2)

Main dipoles in arc cryostat

- Time for the energy **ramp** is about **20-30 min** (Energy from the grid)
- Time for regular discharge is about **the same** (Energy back to the grid)



CMS meeting 8 May 2009

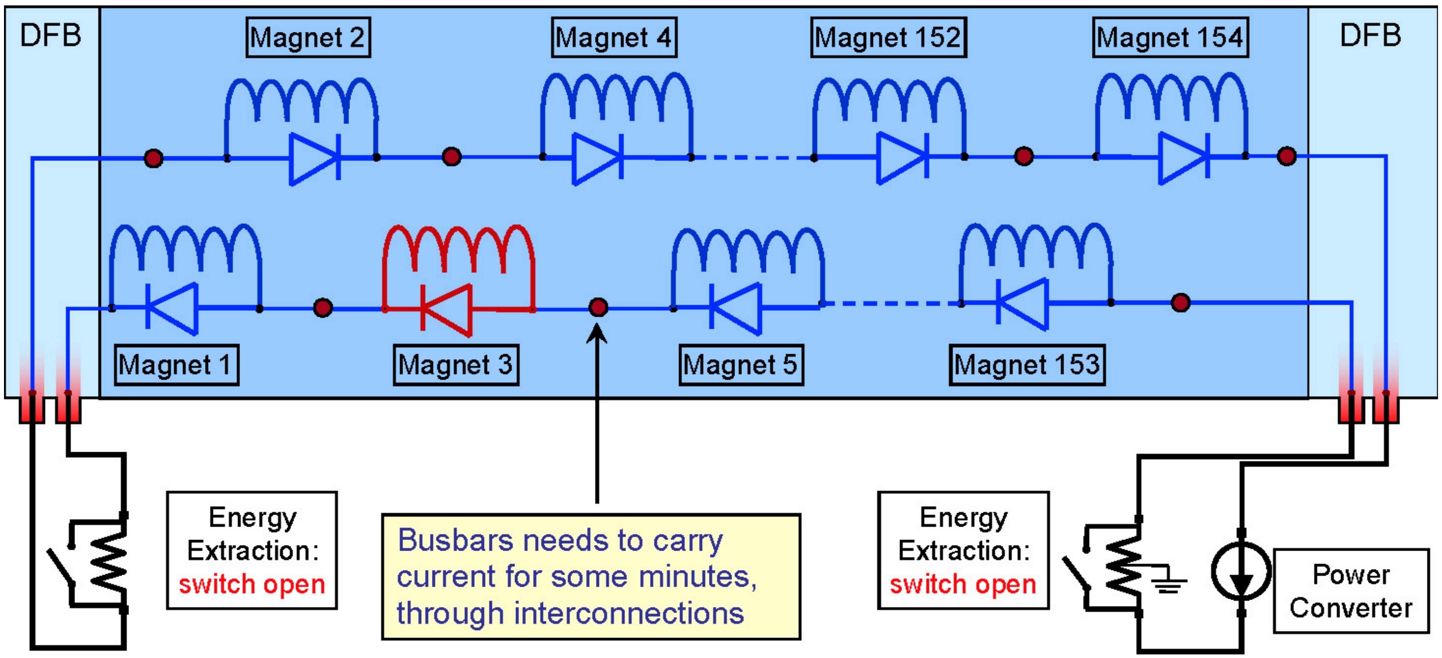
Quenches

- **Superconducting magnets can become normally conducting – a "quench"**
  - Only takes mJ/gram to do it
    - Stray beam, or slight motions of the conductor
- **Magnets, and all cold conductor, must be protected**
- **Quench protection**
  - Quench detected by measuring voltage across magnet and comparing to other magnets, inductance weighted
  - If resistive voltage is detected, heater strips in the magnet are fired
    - Distributes the energy of the magnet (~3.5 MJ) through the whole magnet
  - PS are shut off and current routed through external resistors
  - Mistakes were made at LHC

Quench Protection & Energy Extraction

Main dipoles: magnet protection

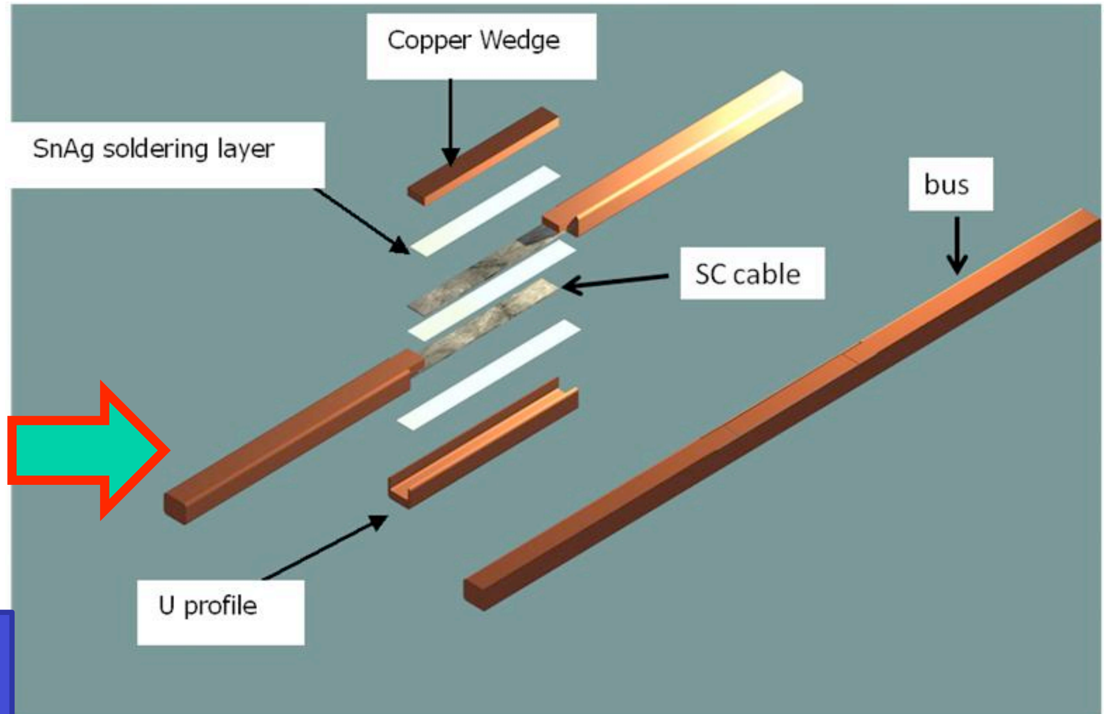
- Quench detected: energy stored in magnet dissipated inside the magnet (time constant of 200 ms)
- Diode in parallel becomes conducting: current of other magnets through diode
- Resistance is switched into the circuit: energy of 153 magnets is dissipated into the resistance (**time constant of 100 s for main dipole magnets**)



CMS meeting 8 May 2009

LHC Inter-magnet Joint

Interconnect splices are not protected by diodes and in the case of a problem all the current of the circuit passes through them with a decay time of ~100 s



Nominal interconnect splice resistance:

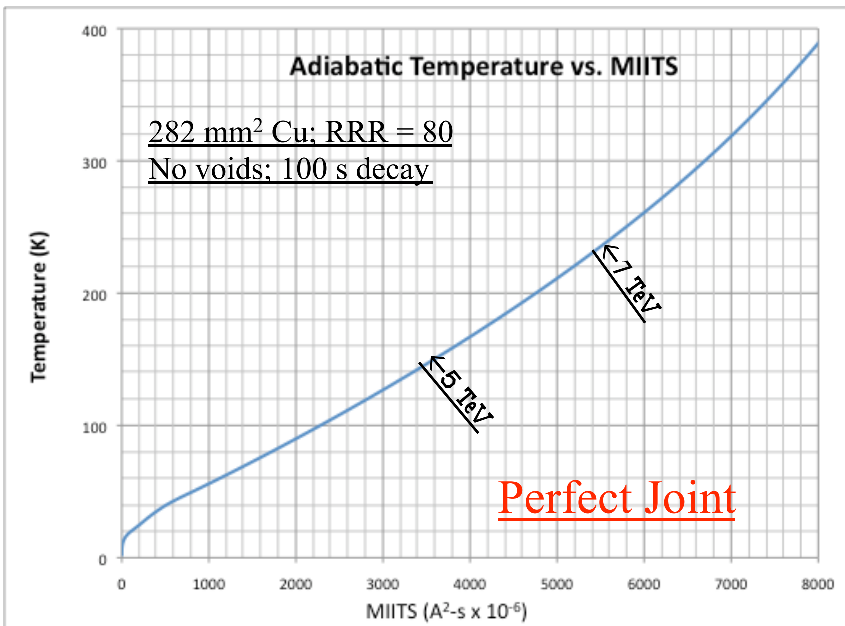
- At cold: **300pΩ**
- At warm (300K): **10μΩ**

The bus & joint is designed to take the decaying current for 200 seconds

LHC Temperature vs. MIITS

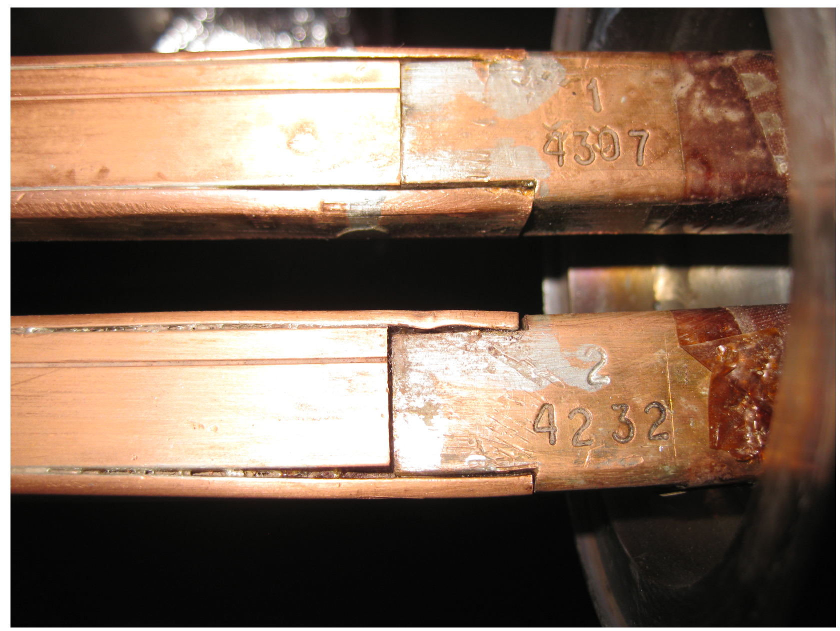
$$\int_{t_0}^{t_1} I(t')^2 dt' = A \cdot A_{cu} \cdot \int_{T_0}^{T} \frac{c(T')}{\rho(T')} dT' \equiv F(T)$$

I^2t in units of 10^6 A^2-s (MIITS)



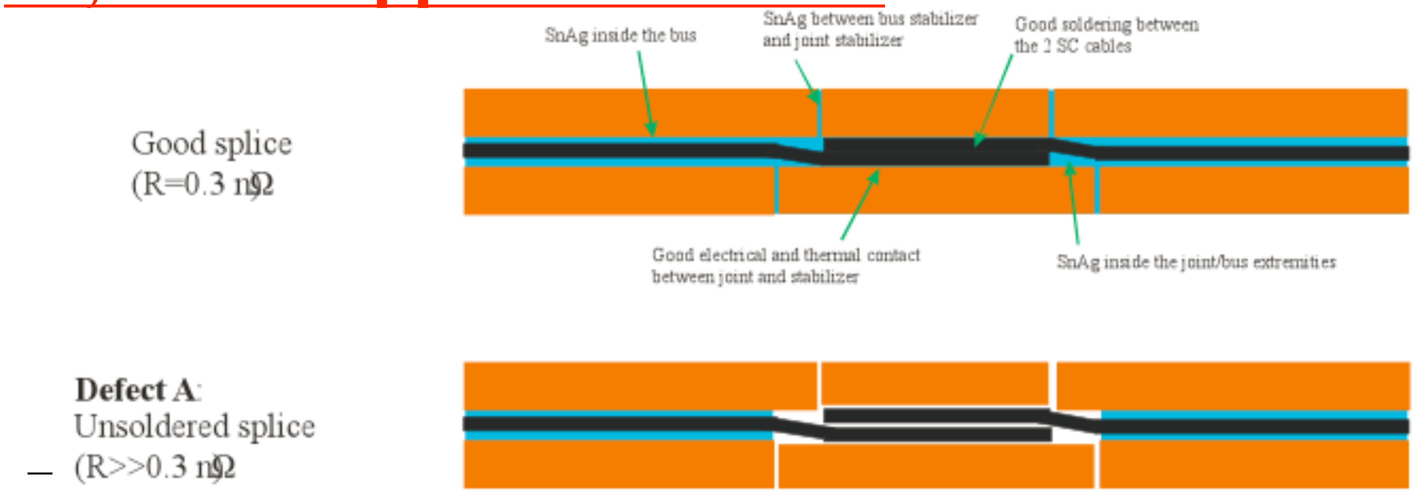
- **Good joint = No problem**
- **So, what happened on 9/19?**

- **Not all joints are perfect**



LHC Temperature vs. MIITS

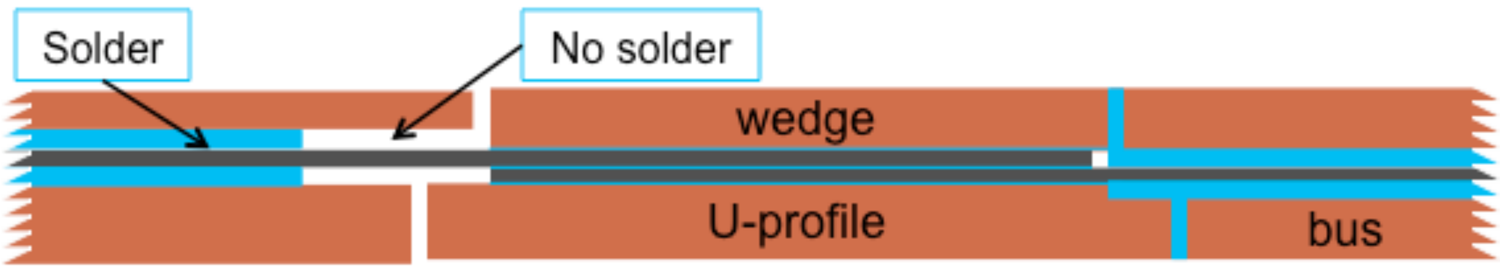
- **So, what happened on 9/19?**



  - Bad thermal contact; little quench propagation outside of ~150 mm
    - 1 V threshold @ 8700 A; T>1500 K
- **Is this safe with new Quench Protection System (QPS)?**
  - 300 μV threshold @12,000 A; T< 200 K
- **New QPS protects against this type of failure.**

LHC Temperature vs. MIITS

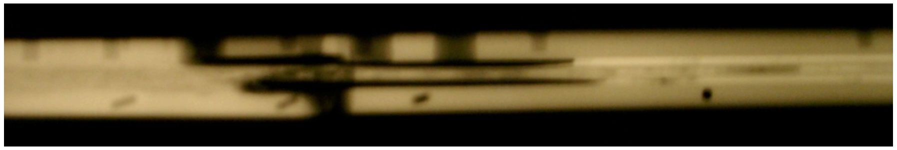
- **But wait; there's more!**
- **The Verweij / Pfeffer conjecture**
  - Not actually a conjecture, because it's a fact
  - Voids & poor electrical contact that forced current through SC



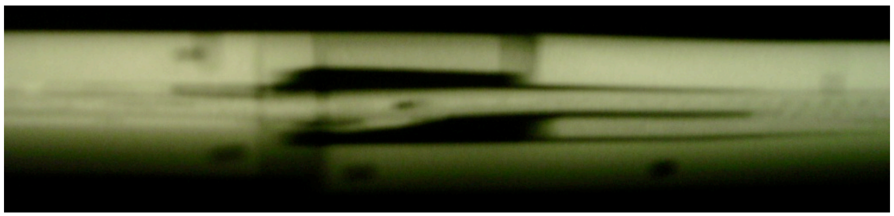
  - The final temperature depends on the length of the void
    - Cable blows up during dump, even at 300 μV detection if void is

    > Some critical length
  - **What is the safe energy to run at?**
    - It depends on the length of voids, which are characterized by their 300 K resistance
    - There are hundreds of voids in the LHC interconnects

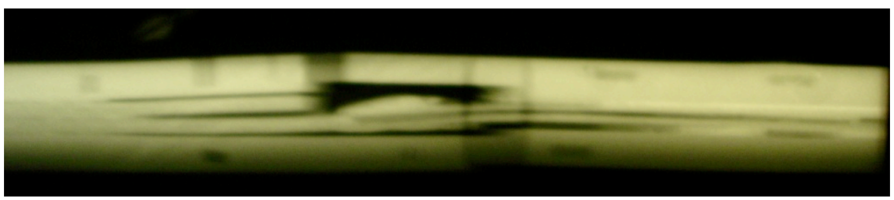
Sample Joint X-Rays



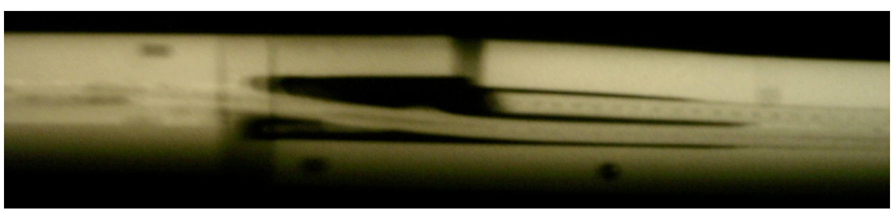
Sample 1 (61 μΩ)



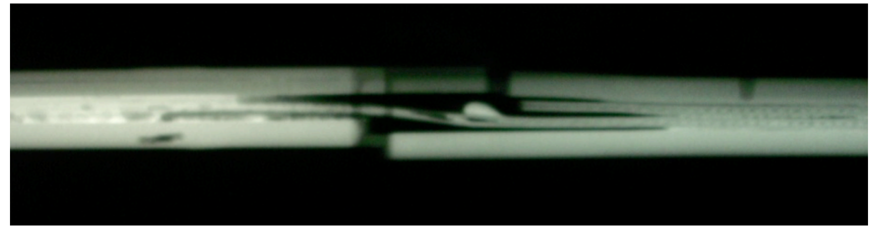
Sample 2A left (32 μΩ)



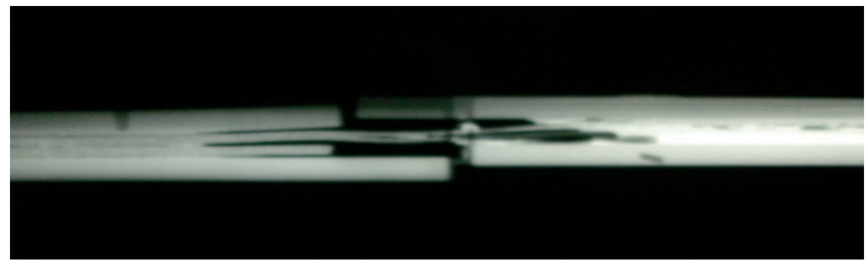
Sample 2A right (43 μΩ)



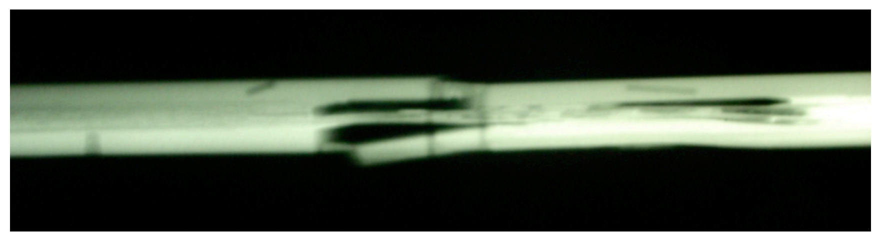
Sample 2B (42 μΩ)



Sample 3A left (26 μΩ)



Sample 3A right (43 μΩ)



Sample 3B (21 μΩ)

Pictures by J.-M. Dalin

What was done wrong?

- **Conceptual mistakes**
  - Superconductor and bus not protected everywhere
  - Assumed all installation work would be perfect
  - Assumed bypass bus could not spontaneously quench
  - Poor estimate of the maximum credible accident
- **Design errors**
  - Joints not overlapped enough (contact area)
  - Joints not clamped
  - Joints not easily inspected
  - Wrong installation solder; same melting temperature as bus solder
  - Not enough voltage taps
- **Execution errors**
  - Installation done by piecework, jeopardizing quality
  - Poor quality assurance plan and sleepy quality control
  - Poor equipment maintenance; some equipment malfunctions

Possible Solutions

1. **Somehow reduce the current decay time constant**
    - Install a cold or warm bypass so the bus is protected in series with the magnets. Then $\tau \leq 1$ s
        - Install safety leads in some short straights. Probably not feasible
        - Or, bypass & quench the whole sector. Potentially dangerous.
    - Break up the circuit so the decay time constant is shorter
        - May not be good enough for any reasonable time constant

2. **Limit the beam energy to a "safe" level**

   This is acceptable for some period of time, but not forever

4. **Make every splice "perfect," or, at least, good enough**

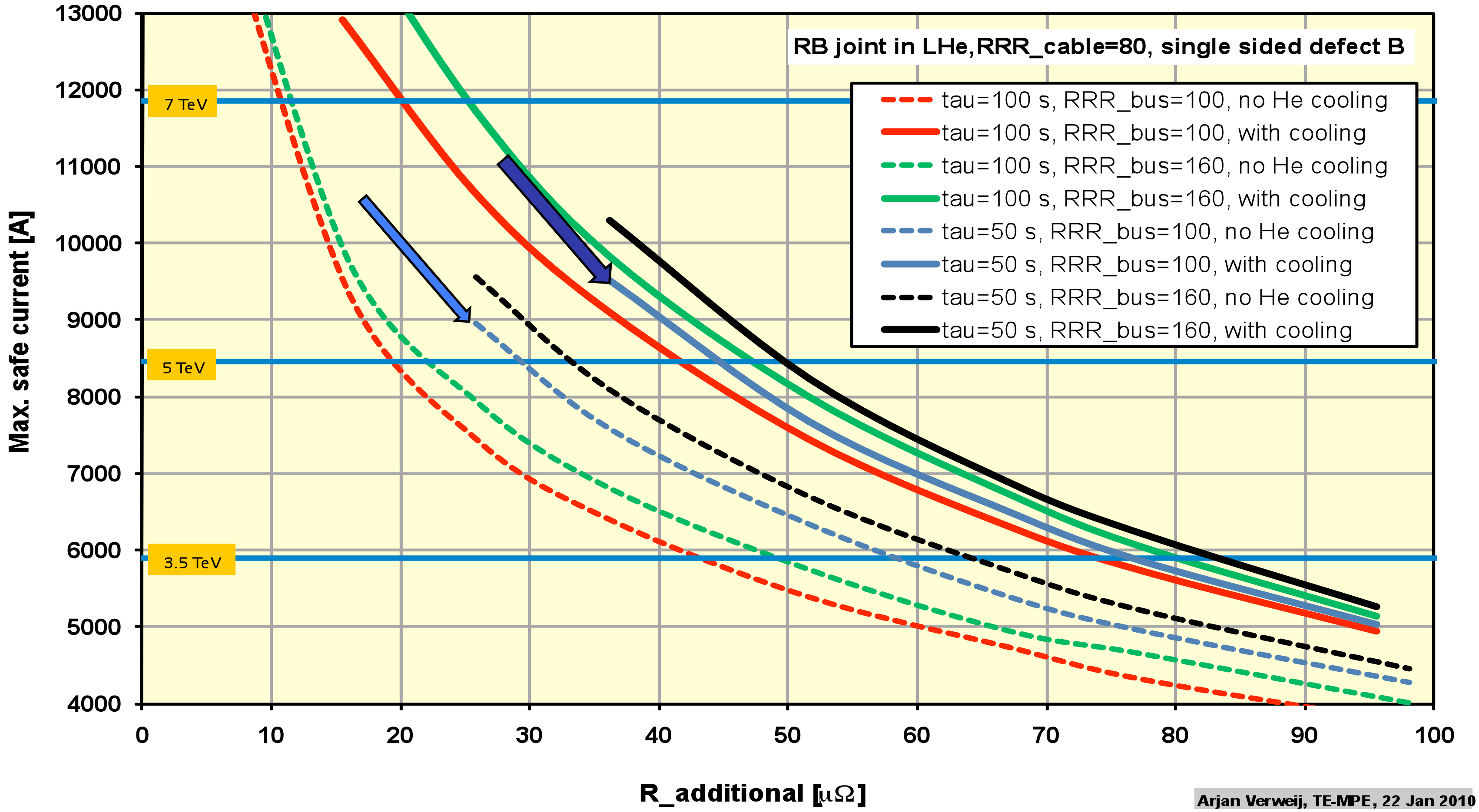
- **It seems to me that only option 3 is viable**
    - With a bit of option 2

Question: Can we find every bad joint or will we have to repair them all?

Finding Bad Joints

- **Superconducting splices**
  - This is taken care of with nQPS and 300 μV threshold
- **Finding bad bus joints; Not so easy**
  - Quality of joint expressed in μΩ above nominal at 300 K (10 μΩ) = R_{addit}
  - Voltage taps only at quads ~100 m apart
    - A "Segment," the distance between voltage taps, is the smallest length measurement that can be done without opening the cryostat
    - Segment = Two or three joints in dipole bus; eight (or more) in quadrupole bus
  - Cannot be done if cable is superconducting
    - Must warm to > 20 K;
      - RRR not well known; Temperature not well regulated
      - So, must measure at ~300 K
  - Measuring across a segment not very accurate at the tens of μΩ level
  - Most accurate way is to open suspect joints and measure resistance at 300 K.
    - The "R-16" measurement. Accurate to ±1.5 μΩ, but very time consuming.
- **Statistical analysis says there is a 10% chance of a joint with R_{addit} > 90 μΩ**

Safe operating margin?



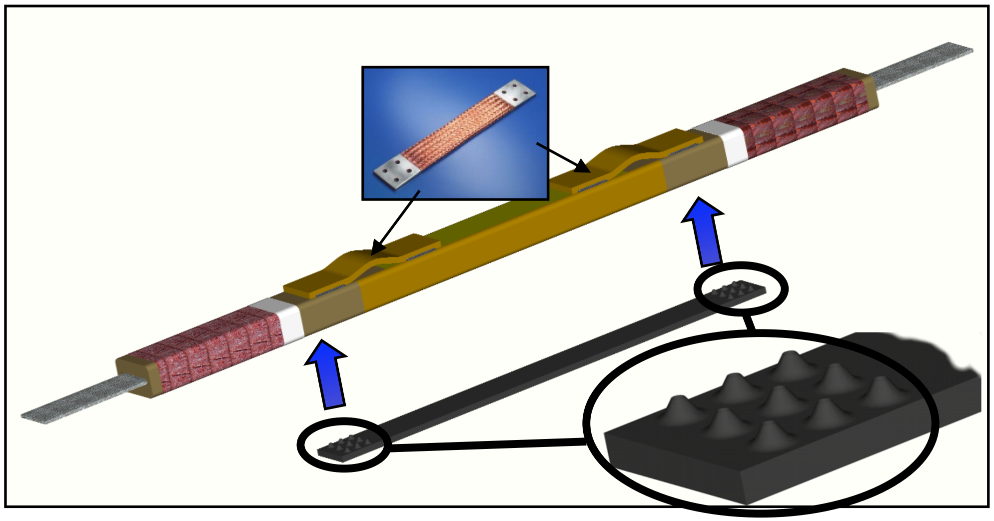
Personal Thoughts

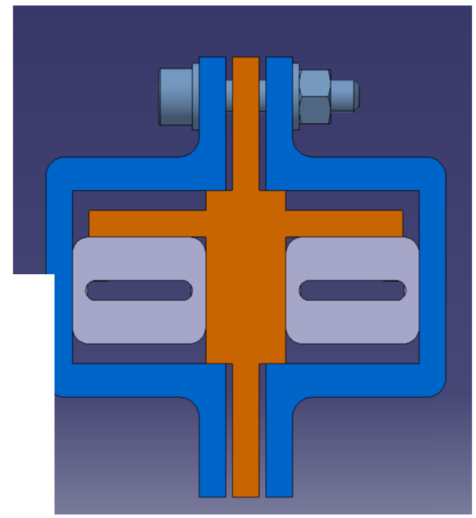
- **Is running at 3.5 TeV safe?**
  - I think it's marginal; CERN thinks it is "just okay"
    - LHC used a non-adiabatic model to determine that $R_{addit} < 76\ \mu\Omega$ is safe.
    - An adiabatic model requires $R_{addit} < 56\ \mu\Omega$
    - It very likely that there are many joints with $R_{addit} > 56\mu\Omega$
    - (In fact, it's likely that there are some joints with that $R_{addit} > 76\ \mu\Omega$
  - Since it takes multiple failures for a disaster, LHC is probably safe

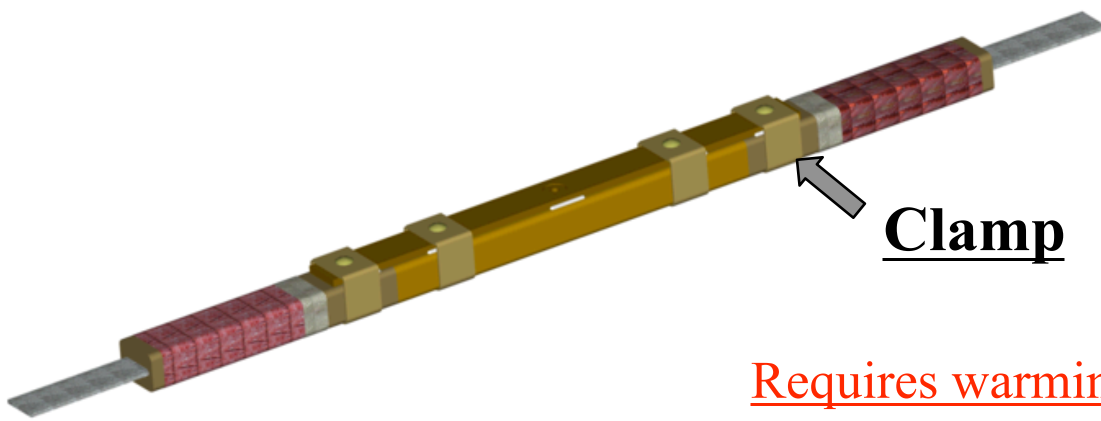
Personal Thoughts - 2

- **What about 5 TeV?**
  - All the "bad" joints have to be fixed
    - "Bad" = $R_{addit} > 25\ \mu\Omega$
    - It is known that there are many joints worse than that
    - There is no reliable way to locate them
  - Not likely to be able to find and repair joints to make 5 TeV running safe
- **7 TeV?**
  - Must fix/modify all the joints in the LHC
  - Will take a 12 month shutdown, at least
  - There is what appears to be a good concept for the repair

Present Repair Concept







Clamp

Requires warming to 300 K everywhere and opening every interface and joint

Chamonix 2010

- **LHC Performance Workshop @ Chamonix**
  - Once-a-year workshop to expose CERN plans to larger audience
- **Main items this year:**
  - Repair scenarios for LHC joints
    - Whether to have only one long shutdown or two shorter ones
    - Whether to try to fix things for 5 TeV per beam
      - (The words “repair” and ”fix” are not actually allowed at CERN, since they would imply that something was not done correctly, which is inconceivable.
      - It’s “consolidation.” as in “Interventions are made to consolidate nonconformities”)
  - Upgrades (I’ll skip these)
    - Injectors
    - Inner triplets
  - Discussions of luminosity profile, safe energy and schedule
  - Other stuff (radiation, access procedures, etc., I will skip)

Joint Consolidation

- **Not feasible to do repairs that permit 5 TeV running**
  - So, initial operation at 3.5 TeV, which was presented as "just safe"
  - The experiments strongly favored a long run at 3.5 TeV; at least 1 fb^{-1} (1fb^{-1} = number of collisions required to see one event with a cross-section of 1 fb = 10^{-39} cm^2)
    - To surpass the Tevatron (Tevatron accumulates 10 fb^{-1} (@2 TeV) by end 2011)
    - It did not seem useful to try to upgrade the machine to 5 TeV during a short shutdown that would break up the run period
  - A run of 1 fb^{-1} or ~ 1.5 years, whichever came first
  - A long shutdown (>1 year) starting in late in 2011
    - No beam in 2012
- **This is a challenge to the Tevatron**
  - Should we extend our collider run, presently scheduled to stop at end of 2011

Long Shutdown

- **Make the LHC capable of 7 TeV operation**
  - This involves opening every interface, installing the shunt and clamp and repairing obviously bad joints. 6 joints/interface
  - There are many other types of joints (DFBs, etc.) and splices that may need modifications
  - Install clamshells of Vetronite (a conducting composite) around the beam tubes in the interfaces.
    - To prevent an arc from penetrating the beam tube.
  - Install more rupture disks, some fast-acting valves, etc.
  - Vacuum relief ports on every dipole cryostat. (this is already ~ half done)
- **This is the minimum that should be done**
- **Will the LHC ever get to 7 TeV/beam?**

Extra Slides

Safe Operating Energy

Energy	τ_{RB} [s]	Max. $R_{addit,RB}$ [$\mu\Omega$]	τ_{RQ} [s]	Max. $R_{addit,RQ}$ [$\mu\Omega$]
3.5 TeV	50	76	10	80
5 TeV	75	43	15	41
7 TeV	100	11	20	14

- **3.5 TeV operation is "just OK" wrt estimated worse splice of 90 µΩ: CERN Conclusion**
  - **Conservative assumptions for RRR, ⇨ ongoing tunnel measurements**
  - ***Some assumptions not so conservative (PJL)***
- 5 TeV operation requires repair (and previous localization !) of the highest resistance outlier splices
  - High current pulsing /thermal amplifier diagnostics?
- **7 TeV operation requires extensive consolidation of splices for safest long-term performance**
  - Segment measurements at warm (or any other temperature) are not accurate enough to detect these small resistance values
  - **R_{addit} may degrade during the lifetime of the LHC**
  - Especially for small resistances, the measured R_{addit}(300 K) may not be representative for R_{addit}(10 K)
  - A shunt has to be added on all 13 kA to operate at 7 TeV

A. Verweij

Statistical analysis says there is a 10% chance of a joint with $R_{addit} > 90\ \mu\Omega$

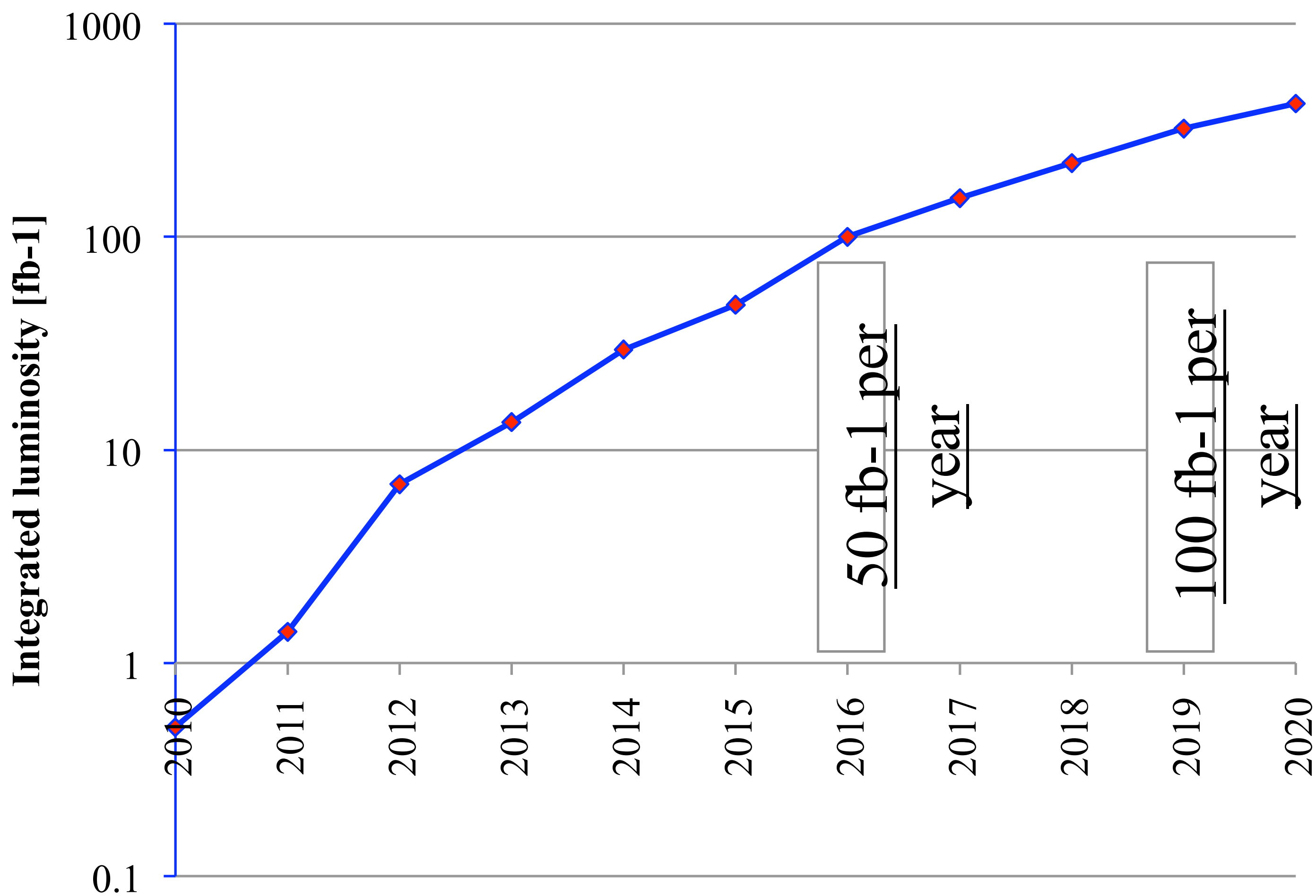
Safe Running @ 7 TeV

- Safe 13 kA operation requires $R_{addit,RB}$<11 μΩ and $R_{addit,RQ}$<14 μΩ.
- Proper quench protection is usually based on an adiabatic approach which further decreases the maximum R_{addit} to 8 and 13 mW.
- One can be sure that there are many hundreds of defects with larger R_{addit} in the machine
- 'Segment' measurements at warm (or any other temperature) are not accurate enough to detect these small values.
- R_{addit} may degrade during the lifetime of the LHC.
- Especially for small resistances, the measured R_{addit}(300 K) may not be representative for R_{addit}(10 K).

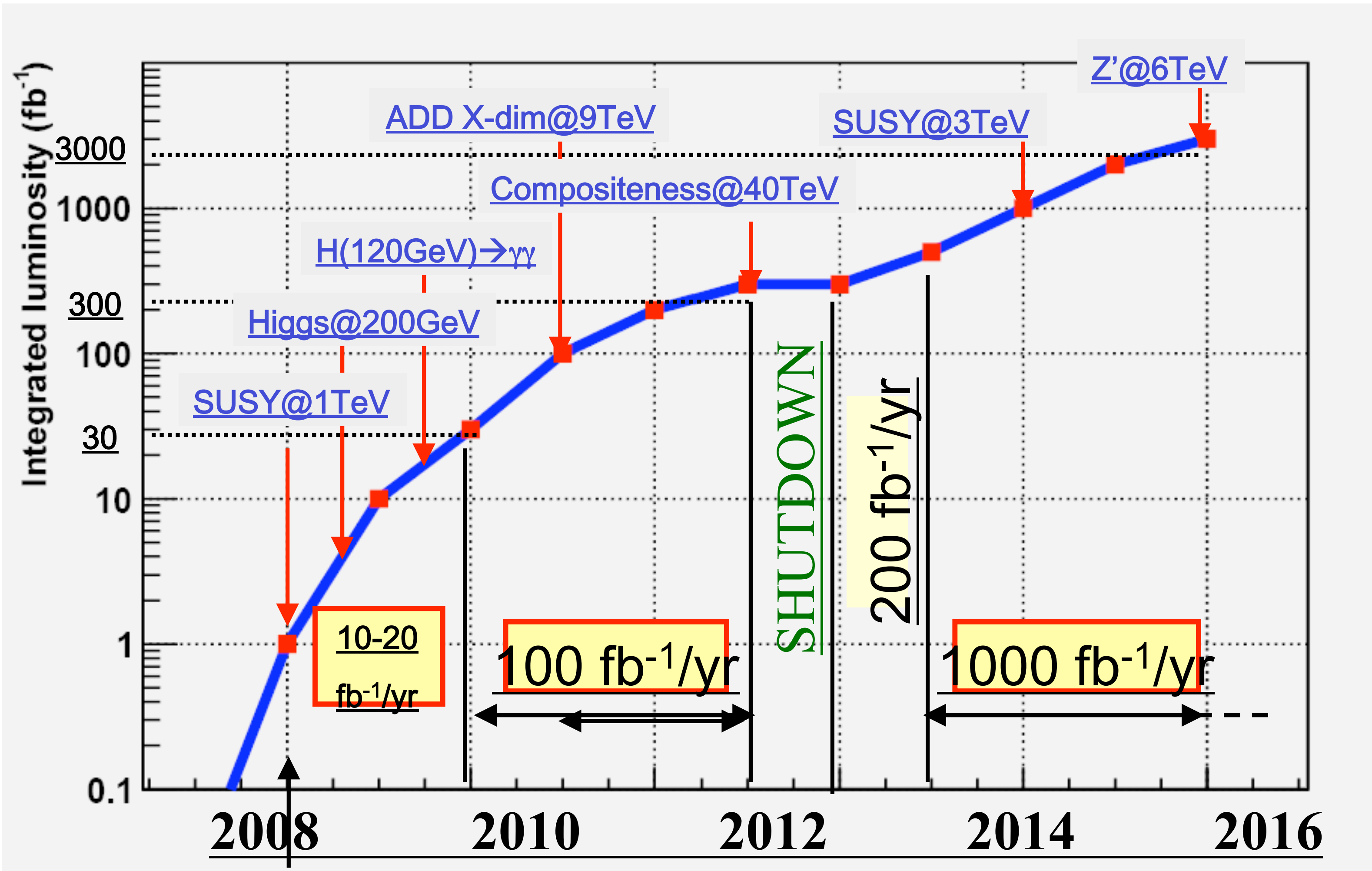
! Conclusion: For safe running around 7 TeV, a shunt has to be added on all 13 kA joints. Joints with high R_{addit} or joints with large visual defects should be resoldered and shunted.

Luminosity Estimates

(Thanks to M. Lamont)



In comparison with…



Upgrades 1

- **Injector upgrades - PS2** (50 GeV) **& SPL** (Superconducting Proton Linac)
  - Two reasons for injector upgrades
    - More intensity for the LHC
    - The PS is 50 yrs old and will be hard to keep running
  - However:
    - Intensity limitations are set by various instabilities in the SPS, not the injectors
      - This was known for many years. Why now?
    - The only 50 yr old things in the PS are the magnet yokes, and they are being slowly consolidated. Everything else has been replaced at least once.
    - Since the upgrades would not be operational for at least 10 yrs, the PS and Booster would have to be made to run another 10 yrs. Why not make them ready to run another 20 yrs?
- **Hence: No new PS2 and no new SPL**
  - **"Saves" an estimated $1.5 billion**

Upgrades 1.5

- **Hence: No new PS2 and no new SPL**
  - This had obviously been decided in advance and presented
    - There was some argument, mostly from Roland Garoby
  - Instead, there are other approaches
    - Work on the SPS limitations
    - Possibly increase the energy of the PSBooster
  - In the end, the LHC beam intensity is determined by machine protection, i.e. collimators
  - **All this will take some fraction (half?) of the $1.5 billion**

Upgrades 2

- **New inner triplets at IR1 (ATLAS) & IR5 (CMS)**
  - Three reasons for new inner triplets
    - Larger aperture allowing lower β^* and perhaps more intensity
      - The inner triplets are the aperture limitation and determine the collimator settings
    - At some point must be replaced due to radiation damage. Years ago, this was expected to be about 2015.
    - LHC wants to generate spare triplet quad spares by replacing the four sets before they are radiation damaged.
  - However:
    - Schedule is already delayed to 2015 installation, at earliest
    - It will take some years to get back the integrated luminosity lost during the shutdown
    - The inner triplets will not suffer radiation damage until much later than previously thought with the present expected luminosity profiles. Perhaps 2018 – 2020
    - The spares issue was not discussed.
  - The people working on the new inner triplets are the same people who are working on the joint consolidation.
    - This will make the inner triplets at least a year later, to 2016 at earliest
- **The inner triplet upgrade will be "discussed."** **There is no set schedule.**

Conclusions from Steve Myers

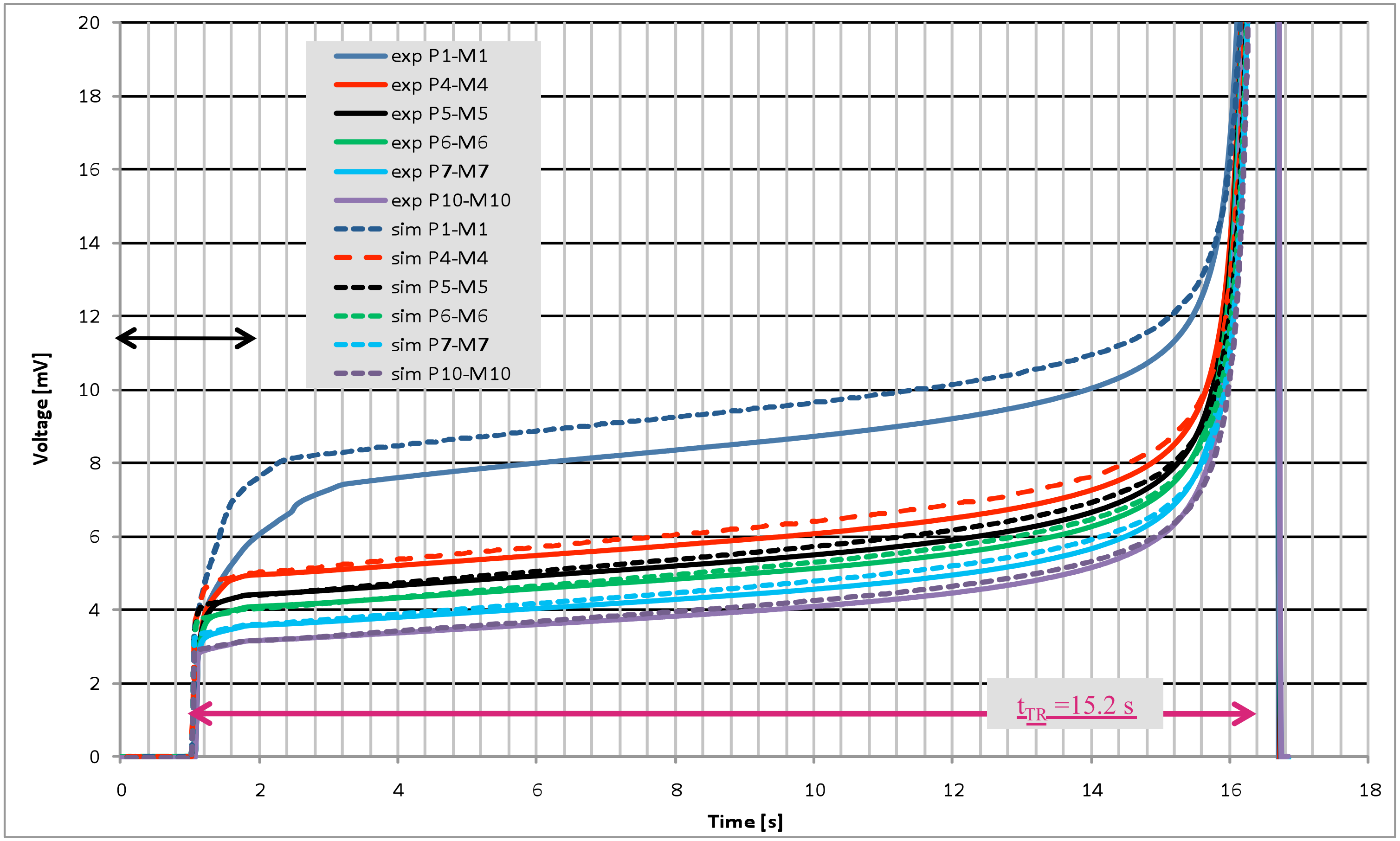
- **The Luminosity Targets set by the detectors are:**
    - $3000 fb^{-1}$ (on tape) by the end of the life of the LHC
    - → $250\text{-}300 fb^{-1}$ per year in the second decade of running the LHC
- **The Upgrades needed to attack these goals are**
    - SPS performance improvements to remove the bottleneck
    - Aggressive consolidation of the existing injector chain for availability reasons
    - Performance improvement of the injector chain to allow phase 2 luminosities
    - a newly defined sLHC which involves
        - luminosity levelling at ~5-6x $10^{34} cm^{-2} s^{-1}$ (crab cavities etc…)
        - At least one major upgrade of the high luminosity insertions

Personal Perspectives

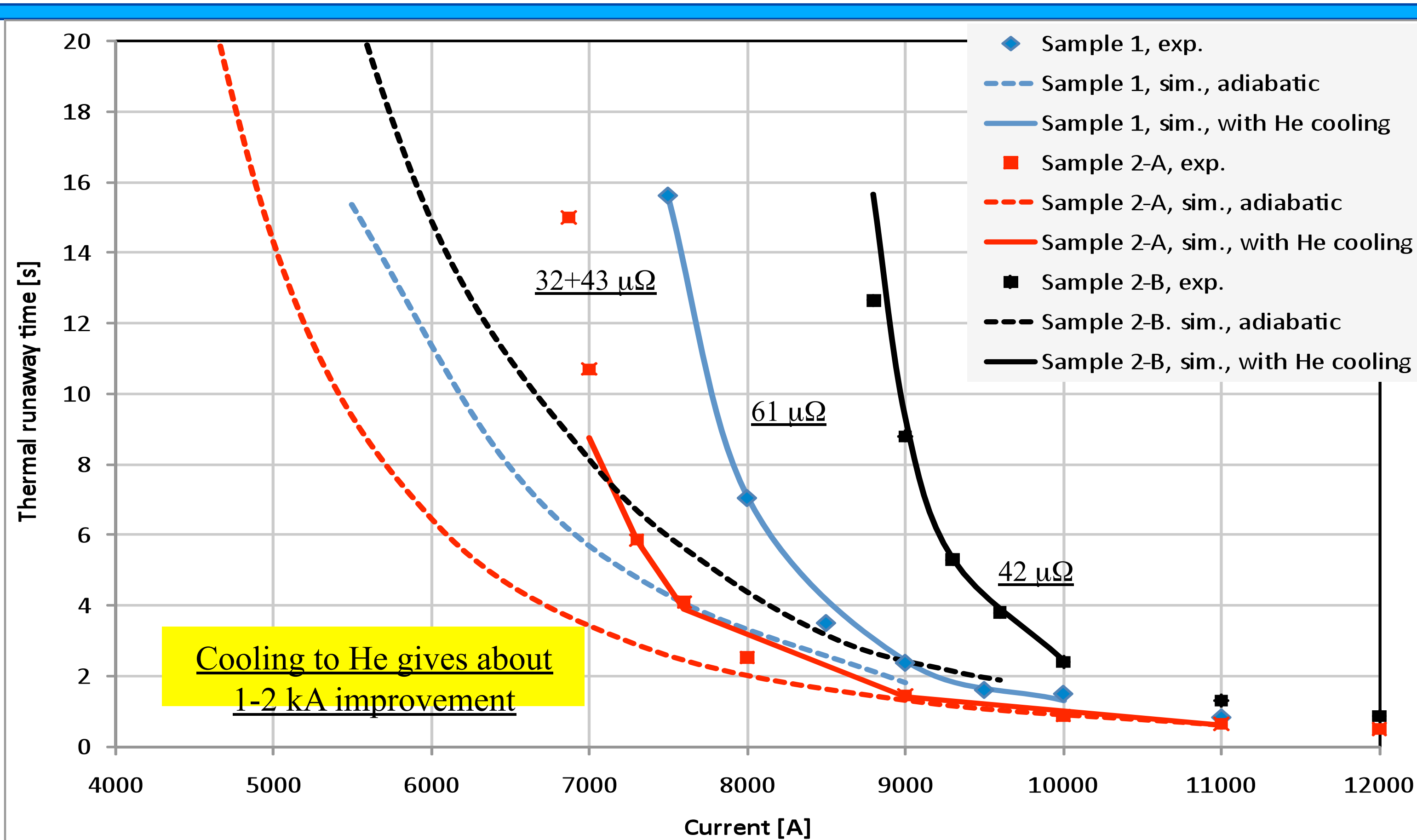
- **The "reconsideration" of the injector & Phase 1 upgrades**
  - Maybe it's just the technical arguments, but…
  - Saves $1.5 billion.
    - Do they expect a decrease in the CERN budget after the loan is paid off?
    - If the budget stays up, perhaps they want to invest in CLIC R&D
      - The next step in CLIC R&D is estimated at ~$700 million
      - The "wish list" of various machine improvements uses the rest
  - What happens to the CERN neutrino program?
  - I think that Linac 4 might also be on the chopping block
  - DOE is unlikely to invest in APUL with no upgrade schedule
    - This "saves" $32 million spread over 4-5 years, roughly half to Fermilab
    - We need to find something for these $ that will keep it in the HEP budget
      - BNL is also affected; perhaps more than Fermilab
- **New schedule & luminosity projections**
  - Should we run the Tevatron longer?

Thermal Runaway

Typical correlation experimental and calculated V(t) curves



Model Fit to FRESCA Data



Correlation experimental and calculated $t_{TR}(I)$ curves.

For each sample the effective heat transfer to the helium is individually fitted